VOL. 12 No. 1, pp. 1-32 JULY 1950

Philips Technical Review

DEALING WITH TECHNICAL PROBLEMS
RELATING TO THE PRODUCTS, PROCESSES AND INVESTIGATIONS OF
THE PHILIPS INDUSTRIES

EDITED BY THE RESEARCH LABORATORY OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN, EINDHOVEN, NETHERLANDS

A SMALL GREENHOUSE WITH ARTIFICIAL LIGHTING FOR STUDYING PLANT GROWTH UNDER REPRODUCIBLE CONDITIONS

by R. van der VEEN. 631.544:581.14.001.5

Experiments carried out under partly unknown conditions have in many cases led to results which are valueless or difficult to interpret, the trouble and time expended on them thereby being lost. The same is the case in the field of plant-physiology, where so many factors are of influence. With the greenhouse described here all the main factors are well under control, so that it will undoubtedly prove valuable for obtaining reproducible results in this field.

The development of a plant depends upon a number of factors, the most important of which are light (its intensity and colour, and also the length of time during which the plant receives light), temperature, the amount of moisture and of carbon dioxide in the air, and the composition of the soil. In order to study the effect of these factors upon plant growth it must be possible to control each one of them separately. Where plants are allowed to grow naturally there can be hardly any question of such a control, particularly in a capricious climate, so that the results of any investigation undertaken will scarcely be reproducible. With the hothouses or greenhouses commonly used it is possible to exercise some control over conditions but not by any means to the extent desired; think, for instance, of the sunlight, which is so unreliable, and the temperature, often rising in the summer higher than one would wish.

Now, in order to make it possible to study the behaviour of plants under well controllable conditions, Philips Laboratories have built a number of "greenhouses" in which the entirely artificial lighting can be adjusted in intensity, spectral composition and duration, and the temperature, the humidity and the CO_2 content of the air can be controlled within certain limits. *Fig. 1* is a sketch of such a greenhouse having a floor space of 1 m × 1.5 m and a height of 1.5 m. Here a description will be given of these greenhouses, one of which is depicted in *fig. 2*.

Light

The lighting is by means of tubular fluorescent lamps (TL lamps) of 40 W, of which there are eleven on each of the two sides and eight at the top. This arrangement gives a very favourable distribution of the light: small plants, or the bottom leaves of larger ones, are not overshadowed by tall plants or, respectively, by the top leaves. When all thirty lamps are alight the intensity of the light is approximately equal everywhere inside the hothouse, amounting to about 60-70 W/m² (10,000-12,000 lux).

The lamps can be switched on and off in groups of three, so that one can work with lower intensities. The lamps on the two sides alone yield more than sufficient light for the normal growth of most plants, the wattage then amounting to about 1 kW per 1.5 m² floor area. Only in the case of some tall-growing plants, like the Poinsettia, was it found desirable to use also the top lamps.

As to the spectral composition of the light, this can be greatly varied by employing different kinds of TL lamps. In the first place there are the normal types available, known as "warm-tone", "white" and "daylight", the spectrum of the first-mentioned type containing a relatively large amount

of red and yellow, whilst that of the "daylight" type contains a fair amount of blue; the colour temperatures of these three types are respectively about 2900, 4000 and 6500 °K. Then there are other, special, TL lamps that can be used, which are lined with phosphors producing, for example, a bluish, greenish or reddish light. By mounting different lamps in the same greenhouse a light can be obtained in practically any desired tint.

Temperature

Although TL lamps radiate comparatively little heat, the temperature inside the greenhouse might rise to too high a level (up to 35 °C with normal ambient temperature) if there were no means of carrying off the heat. Provision has therefore been made for this by arranging for tap-water to flow down the outer side of the glass panes separating the TL lamps from the space within which the plants

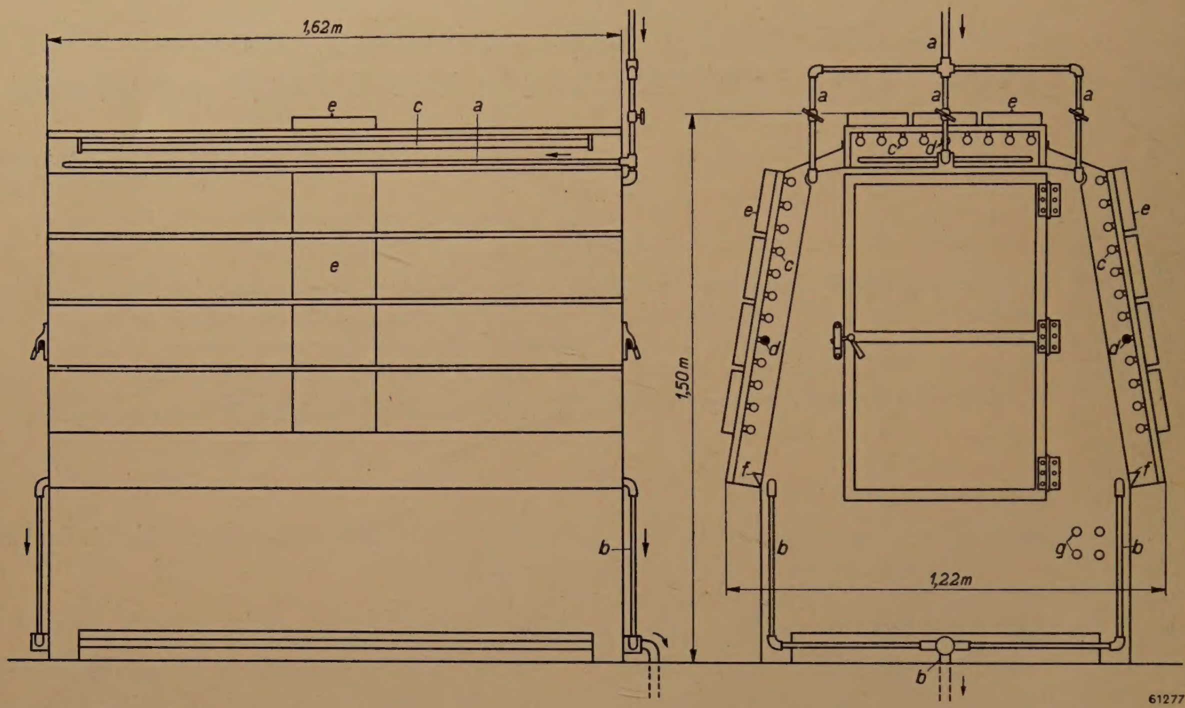


Fig. 1. Sketch of the greenhouse, front and side views. *a* inlet of pipe water for cooling, *b* water outlet, *c* TL lamps (30 in number), *d* mercury lamps (three), *e* starters for the lamps (in groups of three), *f* discharge channel for the cooling water, *g* openings for carrying off condensation water and inlets for air, for CO_2 and for the electric current for heating.

are growing. By means of cocks in the inlet pipes the temperature inside the greenhouse can be regulated between 35 °C and 17 °C. While the TL lamps are switched off the temperature level can be maintained by switching on some incandescent lamps mounted under the floor of the greenhouse so that their light does not reach inside.

At first some trouble was experienced from algae growth in the cooling water. These algae come from germs which are always present in tap-water. They form a green deposit on the glass and make it necessary to clean the panes thoroughly at least once a week. This algae growth has now been prevented by mounting between the TL lamps on each of the two sides and at the top a mercury lamp (TUV lamp, *d* in figs 1 and 3), the ultra-violet rays from which kill the algae; the plants inside the greenhouse are not affected by these ultra-violet

In the designing of the greenhouse account has been taken not only of the possibility of lighting it with TL lamps, but also of the possibility of lamps being used which radiate too much infra-red for plants, such as high-power incandescent lamps. For the latter case provision has been made for a relatively deep layer of water to be introduced at the top of the greenhouse with a view to absorbing the greater part of the infra-red rays coming from the lamps installed above the water.

Another very important factor is the length of time during which the plants are daily exposed to the light [1]). This period of time can be set to any length by means of a time-switch (seen in fig. 2).

[1]) For some of the problems relating to this photoperiodicity see, for instance, R. van der Veen, Influence of light upon plants, Philips Techn. Rev. 11, pp. 43-49,1949/50 (No. 2).

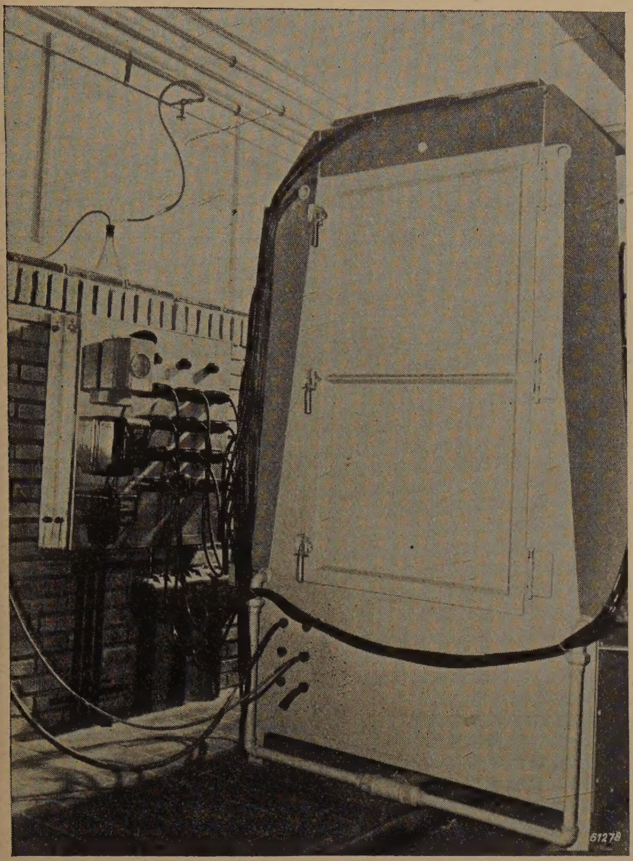


Fig. 2. Front of the greenhouse. On the left the switchboard with plug sockets to which the TL lamps can be connected in groups of three, and with a time-switch for regulating the daily exposure to light. On the left at the bottom: supply lines for air and carbon dioxide.

rays because the glass panes hold them back.

Owing to the cooling there is a great deal of condensation on the inside of the glass panes. The water from this condensation is collected in gutters leading outside the greenhouse; it appears to be free of algae germs, so that — once the panes have been thoroughly cleaned — there is not usually any algae growth, notwithstanding the absence of ultra-violet rays on the inside.

Humidity and CO_2 content of the air; nature of the soil

The greenhouses are connected to a compressed-air line supplying dry air. The more of this air that is allowed to flow through the greenhouse, the lower is the degree of humidity, so that in this way the moisture content of the air inside can be controlled. The normal flow of air supplies an amount of carbon dioxide that is usually sufficient for the growth of the plants, but the CO_2 concentration can be increased when required from a carbon dioxide line likewise connected to the greenhouse. Both lines can be fed from steel cylinders.

Of course attention has also to be paid to the soil in which the plants are set. This factor, however, can be eliminated by applying techniques of water culture, for which provision has also been made in the designing of these greenhouses. One is then independent not only of the climate but also of the soil.

Some results

It is not the place here to go deeply into the results obtained, but some examples may be given to illustrate what can be attained with these greenhouses.

The first experiments were made with cucumber, tomato, Chrysanthemum, Poinsettia, Phlox, tobacco, lettuce and balsam plants. All these kinds of plants showed normal development and were cultivated in the greenhouses from seedlings to flowering and fruit-bearing plants (see, for instance, the

Fig. 3. A greenhouse with Coleus and Petunias. A TUV lamp (*d*) is to be seen between the TL lamps. The ultra-violet rays from this mercury lamp kill the algae which otherwise form a deposit on the glass panes along which the cooling water flows.

Fig. 4. Flowering and fruit-bearing cucumber and tomato plants cultivated from seedlings in the artificial climate of the greenhouse.

tomato and cucumber plants illustrated in *fig. 4*). The influence of the colour of the light is clearly demonstrated by the tomato and sweet-pea plants in *fig. 5*: lack of blue rays results in tall but spindly plants with few branches; light that is rich in blue rays, on the other hand, produces stocky, strong specimens with an abundance of offshoots.

Finally *fig. 6* gives an example of the influence of photoperiodicity upon Coleus, a typically long-day plant (see the article quoted in footnote [1])). Daily exposure to long hours of light (or continuous light as applied in the case of the specimen on the left in the photograph) promotes the development of this plant and gives the leaves a beautiful dark-red colour with a bright-green edge. Nine hours of light per day resulted in a less sturdy plant and the colours were paler.

For botanical and horticultural laboratories a number of greenhouses as described here will prove a useful and valuable addition to the equipment available, especially where physiological experiments are conducted. These greenhouses also lend themselves excellently for experiments in connection with photoperiodicity (see the article referred to in footnote [1])).

a

b

Fig. 5. *a*) Tomato plants exposed to light of a different spectral composition, but otherwise cultivated under the same conditions and of the same age. The plant on the left has been exposed to a predominantly blue light, the middle one to green and the one on the right to red light (the last two with a deficiency of blue). Blue light checks the growth but produces sturdy plants with plenty of offshoots and dark-green leaves. A deficiency of blue light makes the plants grow spindly, with light-green leaves. *b*) The same for sweet peas.

Of course it goes almost without saying that these greenhouses are not intended for horticulture. For nursery work it is generally more advantageous to use normal glasshouses, where full benefit can be derived from sunlight and in which artificial lighting is only employed in the winter months to make up for the shortage of daylight.

Fig. 6. Two equally old Coleus plants (a species of long-day plant), the one on the left exposed to continuous light and that on the right to nine hours light per day but otherwise treated in the same way. The specimen continually exposed to light is stockier and has better coloured leaves.

Summary. In order that experiments can be carried out in regard to the processes of plant growth under well-defined conditions, a greenhouse has been constructed in which a number of factors affecting the plant are fully under control. The entirely artificial lighting is derived from 30 TL lamps giving a uniformly distributed light of 60 to 70 W/m^2 (10,000 to 12,000 lux) in a space of 1 m $\times$ 1.5 m $\times$ 1.5 m. Practically any spectral composition can be obtained by using TL lamps lined with different phosphors. A time-switch provides for an adjustable daily exposure to light. The temperature inside the greenhouse can be controlled between 17 °C and 35 °C by regulating a supply of water from the mains which is made to flow down the outside of the glass walls. Algae growth in the cooling water is prevented by the ultra-violet radiation from three mercury lamps (TUV lamps). When the lighting is switched off the temperature can be maintained by electrical heating. The humidity and the CO_2 content of the air can be separately regulated. Experiments with a large number of species have shown that under these artificial conditions seedlings can be raised successfully to flowering and fruit-bearing plants.

THE INFLUENCE OF TEMPERATURE ON THE FLUORESCENCE OF SOLIDS

by F. A. KRÖGER and W. de GROOT.

535.371

The efficiency of the fluorescence of solids has become of particular importance in illumination engineering since fluorescent lamps came into use. In this connection it is of special interest to know how this property varies with temperature. Generally speaking it appears that efficiency decreases with rising temperature, i.e. at high temperatures fluorescence disappears. A study of this quenching is of importance for gaining an insight into the process of fluorescence, especially when the efficiency is measured in combination with the delay time as a function of temperature.

Introduction

The fluorescence of gases, solutions and solids under irradiation with visible or ultra-violet rays [1] [2] [3]) is closely related to the absorption of that light in the system irradiated. The absorption of a quantum of light (photon) in an atom or molecule of a gas, in an ion or molecule in solution or in a crystal increases the energy of the system, lifting an electron into a higher quantum state. What happens further with such an "excited" electron depends upon the circumstances. In the simplest cases it returns to its original state, the energy obtained from the absorption of a photon being wholly or partly radiated again in the form of a photon. This phenomenon is called fluorescence, and in the case where the absorbed energy is entirely radiated again one also speaks of resonance.

It often happens, however, that the "excitation energy" obtained from absorption is not converted into a photon but into some other form of energy. This may even be the case with a mono-atomic gas. An example is the quenching of the resonance radiation in sodium vapour by the addition of a foreign gas, such as nitrogen. When an excited Na-atom collides with an N_2-molecule there is a chance of the excitation energy being transmitted to that molecule and transformed into kinetic energy, or into vibrational or rotational energy.

In the case of multi-atomic gases and of molecules in solution the process of fluorescence is likewise often replaced by a radiation-less process, the excitation energy being converted into vibrational energy, dissociation energy, or energy required for a chemical reaction, etc.

In the case of acetone vapour it is known, for instance, that only three fluorescence photons are emitted against 100 absorbed ultra-violet photons, the excitation energy from the remaining 97 photons being converted in one way or another into molecular vibrations.

In the case of solutions such a "quenching" may arise when an excited molecule collides with a non-excited molecule of the same kind or with a molecule of the solvent. Therefore, in order to get a highly fluorescent solution a solvent has to be chosen whose molecules have little or no influence upon the excited molecules of the fluorescent substance. There may also be chemical reactions competing with the process of fluorescence, a known example of this being the extinction of the fluorescence of an aqueous solution of fluorescein by KI, whereby an $I(H_2O)^-$ ion is split into $I + H + OH^-$ at the cost of the excitation energy of a fluorescein molecule.

Fluorescence and quenching in the case of solids

In the case of solids the situation is rather more complex. In some cases a fluorescent solid contains atoms or ions, as for instance those of the rare earths or manganese, or groups of atoms, like UO_2 or WO_4, which absorb light selectively. This includes both simple compounds, e.g. CeF_3, $UO_2(NO_3)_2$, $CaWO_4$, and mixed crystals such as $(Zn,Mn)_2SiO_4$. To these belong also substances like ZnS, which become fluorescent by the addition of a small quantity of a foreign metal (Cu, Ag) usually incorporated in the sulphide lattice as chloride (CuCl, AgCl). In the case of sulphide phosphors the permissible concentration of the admixture is very small (10^{-5} to 10^{-1} atom % per molecule of the base material), whereas with manganese phosphors this concentration is greater (0.1 to 10

[1]) W. de Groot, Philips Techn. Rev. 3, 125-132, 1938.
[2]) J. H. Gisolf and W. de Groot, Philips Techn. Rev. 3, 241-247, 1938.
[3]) F. A. Kröger, Philips Techn. Rev. 6, 349-358, 1941.

at. %). The active atom in the admixture (such as Mn or Cu in the examples given) is called the activator.

When such a substance is irradiated and the rays are absorbed at a wavelength within the selective absorption range of the atoms, ions or groups of atoms referred to, then the process of fluorescence resembles very much that taking place in a gas or in a solution. Quenching of the fluorescence might occur here when interaction takes place between the excited atom or ion or the activated group of atoms and the surrounding crystal lattice. The energy accumulated in the centre of fluorescence owing to the absorption of a photon is then entirely converted into vibrational energy of the neighbouring atoms of the crystal lattice and ultimately into vibration of the whole lattice, thus into heat.

Every crystalline substance, whether or not it contains atoms or groups of atoms capable of acting as centres of fluorescence, shows absorption in a certain wavelength range due to the crystal lattice as such and not to any particular centres. When a photon is absorbed in such a wavelength range then an electron of the crystal lattice is brought into a "band" of greater energy. In a few cases also this energy may immediately be radiated again in the form of a photon (an example is the green fluorescence of CdS at —180 °C). In the case of the phosphors just mentioned, however, the excitation energy absorbed by the crystal lattice is mostly first transmitted from the crystal lattice to one of the activator centres present in the lattice.

Sometimes, in addition to the activator, there is also a second kind of atom, the sensitizer, with its own specific absorption. The energy absorbed by this atom is transmitted to the activator centre. An example is calcium phosphate with Ce (sensitizer) and Mn (activator), or calcium silicate with Pb(s) and Mn(a). The sensitizer may itself also cause fluorescence. In the cases mentioned for instance both Pb and Ce fluoresce in the ultra-violet.

With solids, therefore, there may be a great variety of mechanisms of fluorescence due to one or more non-radiating transmission processes taking place between the primary process (absorption of a photon) and the ultimate process of fluorescence (the emission of a photon). Moreover there may also be non-radiating processes whereby the whole of the excitation energy is converted into lattice energy, resulting in quenching and absence of fluorescence. The counteraction between the useful and the useless non-radiating processes determines the quantum efficiency (the number of fluorescent photons per photon absorbed). Since, as will be shown, the probability of any non-radiating process taking place is a certain function of the temperature, the quantum efficiency may either increase or decrease with rising temperature. Given a sufficiently high temperature, quenching processes as a rule predominate, so that ultimately the efficiency is reduced, and at very high temperatures even drops to zero.

Closely related to the influence of temperature upon the quantum efficiency is a second phenomenon, namely the influence of temperature upon the variation of the intensity of the fluorescence with time after irradiation has ceased, thus upon the decay.

What has been dealt with above qualitatively will now be explained quantitatively with the aid of some simple theoretical hypotheses, whilst something will also be said about the measurement of the quantities and the conclusions to be derived from the results.

The relation between efficiency and decay [4])

Suppose we have a centre irradiated with the wavelength that is absorbed by that centre. We then have the situation as represented in *fig. 1.* Through absorption of a quantum an electron is raised from the original state (*0*) to a higher quantum state (*1*). The energy of the centre increases from E_0 to E_1. Let it be possible for the centre

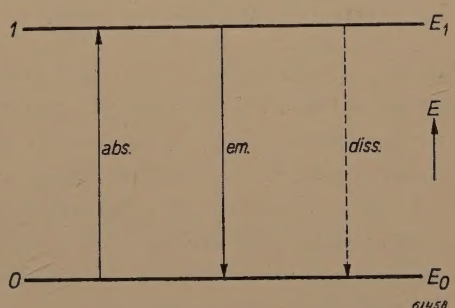


Fig. 1. Absorption and emission in the case of a single excited state (*1*). In addition to the emission (———) also a radiation-less transition (— — —) is indicated. E = energy.

to return to the state *0* under the emission of a photon. If there is no other possibility then the quantum efficiency equals 1, i.e. a photon is emitted for every photon absorbed.

[4]) It is expressly pointed out that in this article by "decay" is meant only the, usually short, decay of the phosphorescence and not the, mostly long, decay of phosphorescence, which is governed by other factors and, for instance, is dependent upon the temperature in an entirely different way.

In fig. 1 it has been assumed, for the sake of simplicity, that the energy of the photon emitted is equal to that of the absorbed photon. This is the resonance, already mentioned, occurring in the case of mono-atomic gases (e.g. sodium vapour).

In all other cases, as with molecules and especially with solids, the situation is usually more complicated (see *fig. 2*). Owing to the absorption of a photon the centre undergoes a change into the state *1*. Usually this absorption is immediately

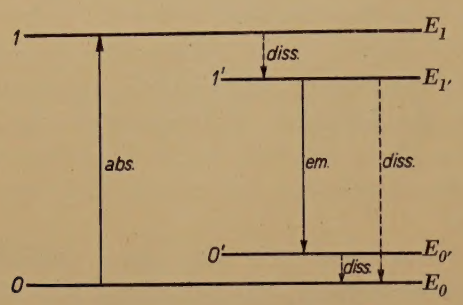


Fig. 2. Explanation of the difference in frequency between emission and absorption in composite systems (molecules in solution, and solids: Stokes's rule). Radiation-less processes are represented by dotted lines.

followed by a non-radiating transition to a lower state of energy *1'*. The states *1* and *1'* may, for instance, be two vibrational states belonging to the same electron state. The emission process will be a transition from the state *1'* to the state *0'*, which usually differs from *0*. This is immediately followed by the transition $0' \rightarrow 0$, again without emission.

The energy differences $E_1 - E_{1'}$ and $E_0 - E_{0'}$ are imparted to the crystal lattice as vibrational energy. As a result the emitted quantum $h\nu_{em}$ is less than the absorbed quantum $h\nu_{abs}$ ($\nu_{em} < \nu_{abs}$ or $\lambda_{em} > \lambda_{abs}$, Stokes's rule). This results in a decrease of the energy efficiency in the ratio ν_{em}: ν_{abs}, even if each absorption process leads to the emission of a photon. The quantum efficiency however remains equal to 1.

Let us now consider the process of fluorescence as a function of time. The number of centres in the state *1* is denoted by n and the number of photons absorbed per second by A. Further, for an electron in state *1* the probability of a transition to the original state under the emission of a photon in the interval of time dt is taken to be equal to $\gamma_f dt$. For n we then have the equation

$$dn = A\,dt - \gamma_f n\,dt\,,$$

or

$$\frac{dn}{dt} = A - \gamma_f n\,. \quad \ldots\ldots \quad (1)$$

When irradiation is continued a long time, a stationary state is reached for which $dn/dt = 0$ and thus n is constant ($= n_0$):

$$n_0 = A/\gamma_f.$$

The number of photons emitted per unit of time is then $\gamma_f n_0 = A$, as is obvious, since the quantum efficiency is 1.

When the irradiation is stopped at a certain moment and the time is counted from that moment onwards ($t = 0$) then for $t > 0$

$$\frac{dn}{dt} = -\gamma_f n\,. \quad \ldots\ldots\ldots \quad (2)$$

and

$$n = n_0 \exp(-\gamma_f t). \quad \ldots\ldots \quad (3)$$

The number of photons emitted per unit of time then amounts to

$$\gamma_f n = \gamma_f n_0 \exp(-\gamma_f t) = A \exp(-\gamma_f t)\,. \quad (4)$$

Thus the fluorescence decreases exponentially with time, and the greater the value of γ_f, the more rapid is the decay.

This case shows a strong resemblance to the acoustical problem of reverberation [5]) and, further, to a large number of physical phenomena based on a formula similar to (2). In particular we would mention, in view of what follows, the discharge of a capacitor with capacitance C and charge Q via a resistance R, where

$$\frac{dQ}{dt} = -\frac{Q}{CR}$$

and thus $Q = Q_0 \exp(-\delta t)$, with $\delta = 1/RC$. A suitable measure for the duration of the decay or, in the case of the capacitor, the duration of the discharge, is the reciprocal value of the constant occurring in the exponential function (thus $1/\gamma_f$ and $1/\delta$ respectively), i.e. the time in which the quantity in question has diminished to $1/e = 0.37$ of its original value.

Let us assume that in addition to the fluorescence transition a dissipation process is also possible, with probability constant γ_d. This means that the probability of an excited centrum giving off its energy to the crystal lattice, without emission, in the interval of time dt, is $\gamma_d dt$. Then, with constant irradiation,

$$\frac{dn}{dt} = A - (\gamma_f + \gamma_d)\,n\,. \quad \ldots\ldots \quad (5)$$

In the stationary case ($dn/dt = 0$) the number of excited centres is now $n_0' = A/(\gamma_f + \gamma_d)$ and the number of photons emitted per unit of time is

$$\gamma_f n_0' = A\,\frac{\gamma_f}{\gamma_f + \gamma_d}.$$

The quantum efficiency now apparently is

$$\eta = \frac{\gamma_f}{\gamma_f + \gamma_d} = \frac{1}{1 + \gamma_d/\gamma_f} < 1.$$

[5]) See W. Tak, Philips Techn. Rev. 8, 82-88, 1946.

At the same time there is also a change in the time law governing the decay of the fluorescence after the irradiation has stopped, for then

$$\frac{dn}{dt} = -(\gamma_f + \gamma_d)\, n,$$

so that

$$n = n_0' \exp\,[-(\gamma_f + \gamma_d)\, t]\,.$$

The number of photons emitted per unit of time is

$$\gamma_f n = \gamma_f n_0' \exp\,[-(\gamma_f + \gamma_d)\, t] = A\eta \exp(-\varkappa t), \quad (6)$$

in which $\varkappa = \gamma_f + \gamma_d$.

The duration of the decay is now $1/\varkappa$, thus less than it was before. Once the quantities η and $\varkappa$ that have to be determined experimentally have been measured, it is easy to calculate therefrom the quantities γ_f and γ_d that are of importance for the theory. One finds:

$$\gamma_f = \varkappa\eta\,, \quad \ldots\ldots\ldots \quad (7)$$

$$\gamma_d = \varkappa(1-\eta)\,. \quad \ldots\ldots \quad (8)$$

The arguments set forth above were applied a long some time ago by Stern and Volmer to the case of the fluorescence of gases and liquids. Their application to the case of the fluorescence of solids is of relatively recent date [6]).

of a certain wavelength, is projected by a second quartz lens L_2 onto the specimen P. This specimen consists of a thin layer of the substance under test applied to a metal plate which can be either heated electrically or given a low temperature by means of a cooling bath. The specimen is contained in a vacuum bulb of quartz with a view to keeping the temperature as constant as possible and in order to prevent condensation of water vapour on the specimen at low temperatures. The fluorescent light is picked up by a concave mirror Sp and reflected upon a photocell C via a filter F that does not transmit the original ultra-violet radiation. The incident light is measured by replacing P by a plate of magnesium oxide, of course without using the filter F.

With this arrangement it is possible to measure in relative units the intensity of the fluorescent light as a function of the temperature and that of the incident ultra-violet radiation. The ratio of these intensities gives a quantity that is proportional to the efficiency, the "relative efficiency". It is much more difficult to determine the efficiency in absolute units, but in most cases this can be dispensed with, the maximum value of the quantum efficiency being simply taken as equal to 1. For the information required the absolute value of

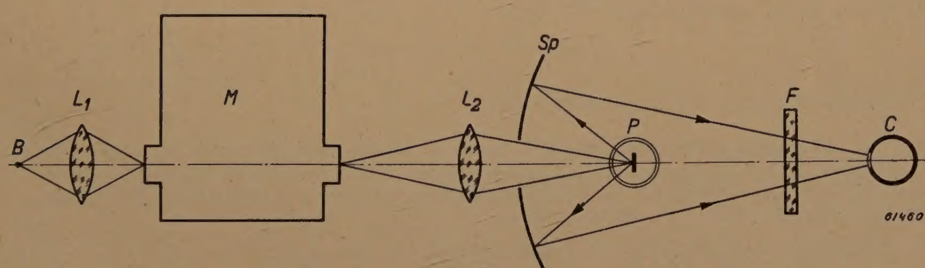


Fig. 3. Arrangement for measuring the efficiency of fluorescence. B source of ultra-violet irradiation, L_1 and L_2 quartz lenses, M monochromator, Sp concave mirror, P specimen, F filter, C photocell.

Measurement of the efficiency

Fluorescence efficiency is measured with the set-up represented diagrammatically in *fig. 3*. The image of a source B of ultra-violet rays, for instance a high-pressure mercury lamp, is projected by a quartz lens L_1 onto the input aperture of a quartz monochromator M. The image of the output aperture of M, which thus emits ultra-violet rays

[6]) L. Brüninghaus, Ann. Physik (6) 2, 55-75, 1948. N. A. Tolstoj and P. P. Feofilov, Doklady Ak. Naoek 59, 235, 1948. K. H. Hellwege, Naturwissenschaften 31, 212-213, 1947. See also the articles quoted in footnote [10]).

the efficiency plays a less important part than the temperature-dependency of the relative efficiency.

The difficulty in determining the absolute efficiency arises from various circumstances. For instance, it is not certain whether the angular distribution of the fluorescent light will be the same as that of the light diffusely reflected by the magnesium-oxide plate. Further, for an absolute measurement the photocell has to be replaced by a bolometer, the sensitivity of which is not dependent upon the wavelength. But even when all this is taken into account there is still an element of uncertainty, because part of the energy absorbed is not used for the process to be studied but is lost in some other way. This will certainly be the case, for instance, when the specimen is mechanically mixed with a neutral absorbing powder (say soot black), but it may also occur with a pure specimen.

On the other hand part of the fluorescent light will be lost in the specimen through absorption. In many cases, however, if disturbing influences are properly taken into account it is found that within a considerable temperature range, in particular at low temperatures, the measured quantum efficiency of the processes studied very closely approximates to unity.

Measurement of the decay

The decay of the fluorescence as a function of time after interruption of the irradiation is measured in the set-up depicted in *fig. 4*, which in many respects resembles that of fig. 3 but is provided with rotating discs having openings cut in them, so that the whole arrangement shows a marked resemblance to the known Becquerel phosphoroscope. The image of the source B is now projected onto the specimen P by two lenses, L_1 and L_2. Here the monochromator is replaced by a filter F_1. The lens L_1 casts a picture of B onto the disc S_1, which has an opening of 90° and thus lets the rays through during one quarter of a revolution and shuts them off during three quarters of that time. In the diagram the instant is depicted when the light has just been shut off and thus the decay begins. The image of the fluorescent strip of the specimen P is formed on the photocell C_1 via the mirror SP_1 and the lens L_3. At the place where the mirror forms an intermediate image is a second disc, S_2, mounted on the same shaft as S_1. This second disc has a narrow radial slit which can be so adjusted that the light is only passed through at the moment that S_1 has revolved through an angle φ from the beginning of the interruption, thus at a moment

$$t = \frac{\varphi}{2\pi} \cdot t_s ,$$

where t_s represents the time of the revolution of the discs. Each time the slit passes through the beam a flash of light is allowed to pass through and this can be measured separately, for instance with the aid of a cathode-ray oscillograph, or integrated over the time (thus as a direct current) by means of a galvanometer shunted by a capacitance. By varying the angle φ (for this purpose S_2 has been made adjustable with respect to the shaft) the intensity of the afterglow can be studied as a function of t. In many cases a time function is found as in equation (6), thus an intensity proportional to exp $(-\varkappa t)$. The logarithm of the intensities found is then plotted in the known way as a function of t, and $\varkappa$ is determined from the slope of the straight line drawn through the points of measurement.

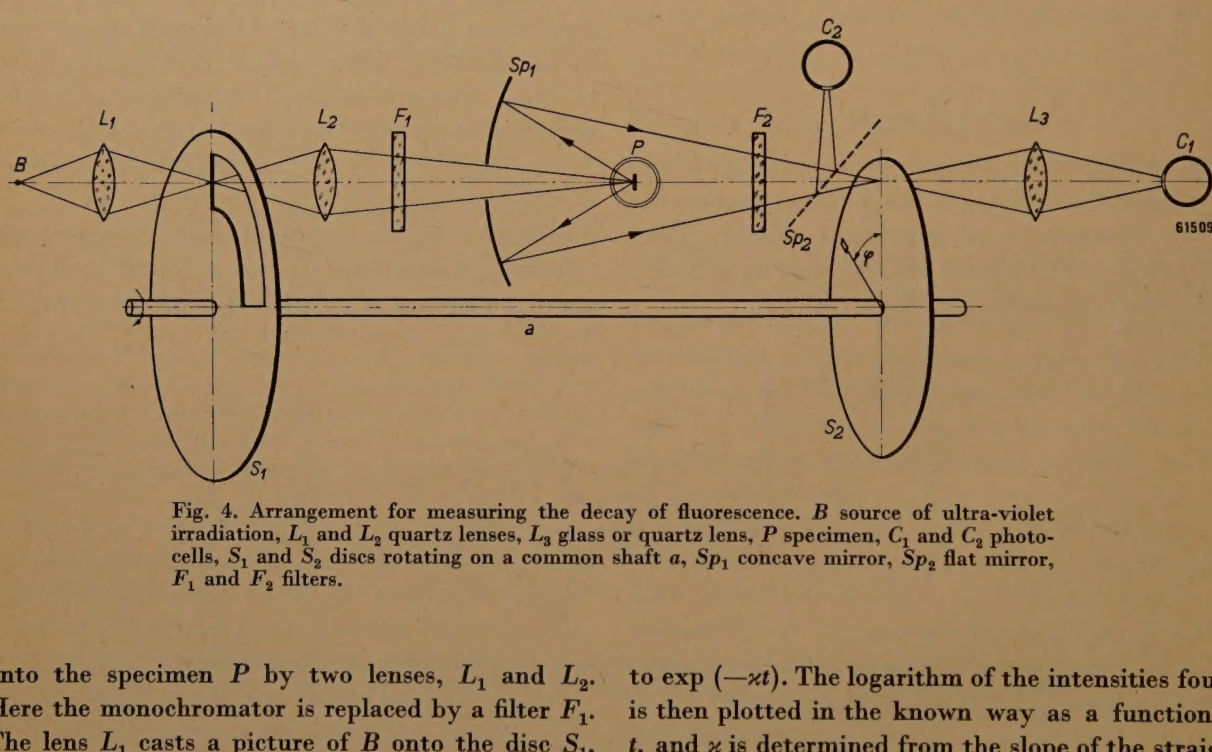


Fig. 4. Arrangement for measuring the decay of fluorescence. B source of ultra-violet irradiation, L_1 and L_2 quartz lenses, L_3 glass or quartz lens, P specimen, C_1 and C_2 photocells, S_1 and S_2 discs rotating on a common shaft a, Sp_1 concave mirror, Sp_2 flat mirror, F_1 and F_2 filters.

Another way to find the intensity as a function of t is to arrange for the light coming from the concave mirror to fall, via a second, flat mirror Sp_2, upon the photocell C_2, the signal from which is fed to the pair of vertical deflection plates of a cathode-ray oscillograph. When the other pair of deflection plates is connected to a linear time base then the screen shows both how the fluorescence increases at the beginning of the irradiation and how it decays after irradiation has ceased, it then being possible to measure and study both these time functions on the screen. When the fluorescence decays according to an exponential function of

time then by this method the time constant $\varkappa$ can be determined directly, by applying an exponential time base. This is done by connecting the horizontal deflection plates of the oscillograph to a capacitor (capacitance C) that is periodically charged and discharged via a resistance R at the rate of the revolution of S_1. The horizontal deflection is then proportional to exp $(-\delta t)$, where $\delta = 1/RC$. If $\delta = \varkappa$, which can be attained by adjusting R, then a straight line is produced on the screen, whilst in all other cases the line is curved. In this way $\varkappa$ can be found very quickly [7]).

A certain, simple case will be taken to show what results are obtained from the combined measurements of efficiency and intensity. As an example we have chosen the fluorescence of ammonium uranyl pentafluoride, $(NH_4)_3UO_2F_5$, irradiated with ultra-violet rays of the wavelength λ = 3650 Å. The fluorescence of this compound is due to the UO_2 group. Both the absorption and the emission spectra consist of a group of narrow bands [8]), the emission bands having wavelengths between 4700 and 6050 Å. In *fig. 5* the logarithm of the intensity of the fluorescence after the irradiation has ceased has been plotted as a function of t for a number of temperatures between —148 °C and +123 °C. It is seen that a number of straight lines are obtained, which proves that the decay

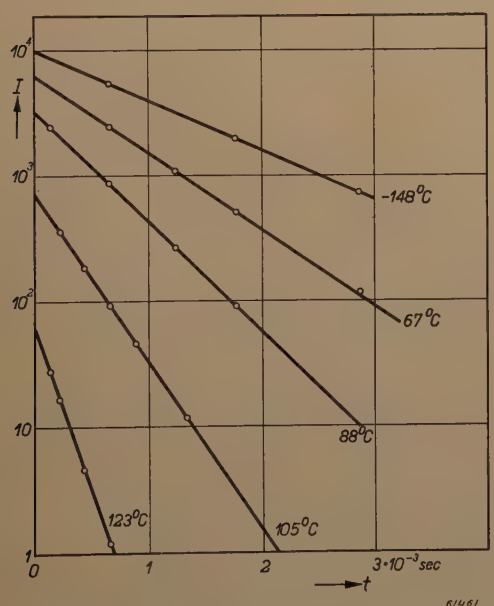


Fig. 5. Intensity of the fluorescent light plotted on a logarithmic scale as a function of time after interruption of the irradiation.

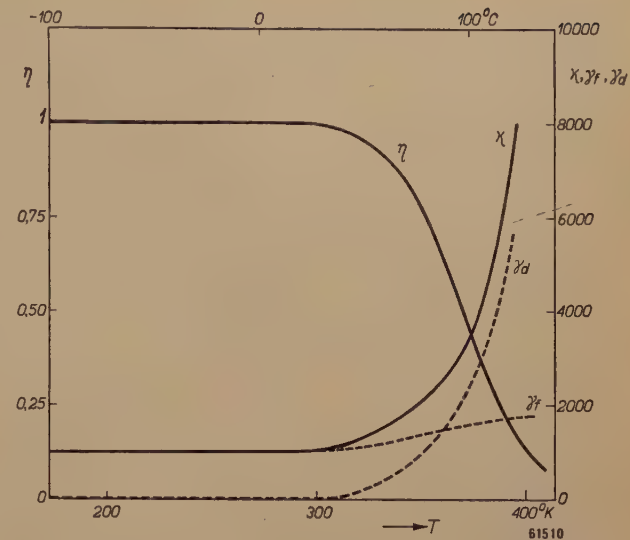


Fig. 6. The efficiency η and the reciprocal decay time $\varkappa$ for ammonium uranyl pentafluoride as a function of the temperature T. The quantities γ_f and γ_d are also plotted.

follows the exponential law $I_t = I_0 \exp(-\varkappa t)$ and also that $\varkappa$ increases with rising temperature. In *fig. 6* $\varkappa$ has been plotted as a function of the absolute temperature T, together with the efficiency of the fluorescence η. Here, for the reasons given above, the efficiency at low temperatures has been taken as being equal to unity. From the values of $\varkappa$ and η the values of γ_f and γ_d have been calculated according to the formulae (7) and (8), and these quantities have likewise been indicated in fig. 6.

Discussion of the measurements

It is seen that γ_f varies but little with T and can, therefore, to a first approximation be regarded as a constant. On the other hand the quantity γ_d, which is practically negligible at temperatures below 20 °C, increases rapidly with T at higher temperatures. In order to investigate what law this increase follows, log γ_d has been plotted in *fig. 7* as a function of $1/T$. It appears that, within the errors of observation, the variation of log γ_d can be represented by the straight line

$$\log \gamma_d = 12.48 - \frac{3570}{T}.$$

Thus γ_d can be represented by an exponential function of the shape

$$\gamma_d = S \exp(-\varepsilon/kT), \quad \ldots \ldots \quad (9)$$

where k is Boltzmann's constant ($k = 1.38 \times 10^{-23}$ joule/°K, $1/k$ = 11.600 °K/eV) and $S = 3 \times 10^{12}$, whilst ε = 0.7 eV.

This points to the fact that a centre already in an excited state requires a certain additional

7) This method of measuring resembles very much a method already described in this journal for determining the acoustical reverberation time; see the article quoted in footnote 5).
8) See also Philips Techn. Rev. 3 (1938), p. 131.

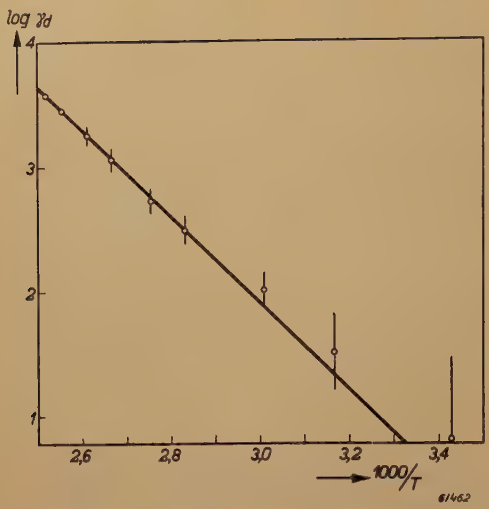


Fig. 7. Logarithm of the dissipation constant γ_d as function of $1/T$ (T = absolute temperature). The vertical lines denote the inaccuracy of the measurements.

energy ε (activating energy) for the non-radiating transition from excitation energy into lattice energy to take place. This hypothesis was introduced long ago by Jablonsky and has more recently been applied by Mott and Gurney to the case of solids. The highly complicated problem was greatly simplified by substituting one imaginary coordinate x for the large number of coordinates corresponding to the numerous degrees of freedom of the centre in the surrounding crystal lattice.

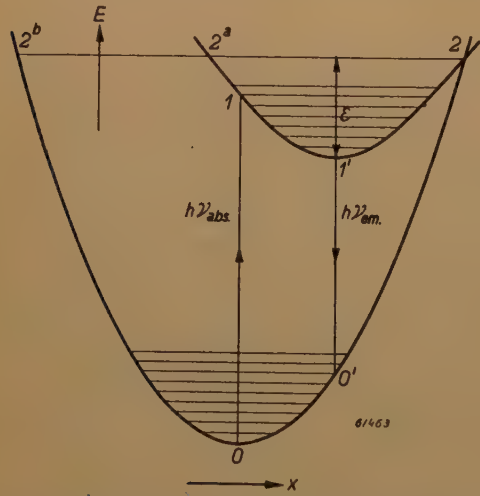


Fig. 8. Model depicting the theory of the quenching of fluorescence in the case of solids, according to Mott and Gurney.

In *fig. 8* the potential energy of the system: centre + immediate surroundings (briefly referred to in the following as "centre") has been plotted as a function of x both for the original state and for the excited state. The minimum of the potential curve represents in each case a state of equilibrium around which vibrations are possible. A number of vibrationary states have been indicated both for the original state and for the excited state. Further there are indicated the energies $h\nu_{abs}$ and $h\nu_{em}$ of an absorbed and an emitted photon (compare fig. 8 with fig. 2). After the excitation *0* → *1* the centre quickly passes into the state *1'*, whereby the vibration energy is imparted to the surrounding crystal lattice. Inversely, in the state *1'* the centre may also draw energy from the crystal lattice, its vibrational energy then increasing. Upon the point *2* being reached, which shows an energy difference ε with respect to *1'*, it is then possible for the centre to pass from the state in which it oscillates between *2* and 2^a into a state which belongs to the lowermost potential curve and represents a very high vibrational condition of the ground state (oscillation between *2* and 2^b). As a consequence of the coupling between the vibrations and the rest of the lattice, which does not find expression in this model, this vibrational energy will then very soon spread over the entire crystal lattice, so that the state *0* is reached without a photon having been emitted. Since the probability for the transition *1'* → *2* is proportional to exp $(-\varepsilon/kT)$, formula (9) is theoretically justified and the physical significance of the "activation energy" ε is explained.

The behaviour described here for the case of the uranyl salt has also been found in a large number of other cases, two of which may be mentioned here, whereby a manganese ion acts as centre of fluorescence, viz: Mg_2TiO_4 activated with Mn present as a quadrivalent ion (Mn^{4+}), and the well-known willemite (Zn_2SiO_4-Mn_2SiO_4), in which Mn occurs as a bivalent ion (Mn^{2+}).

We shall now briefly deal with some cases of fluorescence of solids where the behaviour is more complicated than can be described with the aid of the theoretical hypothesis given above.

Complicated mechanisms of fluorescence

To gain some insight into more complicated cases of fluorescence we must first follow some theoretical considerations. Suppose that (*fig. 9*) in addition to the original state (*0*) there are at the same time two states of excitation (*1*) and (*2*) corresponding to the energies E_1 and E_2 ($E_2 > E_1$), and further that owing to the absorption of a photon there is an electron in the state *2*. We now assume that transitions are possible from *2* to *0*, from *2* to *1* and from *1* to *0*. Each transition may take place either with the emission of a photon or without any radiation. The probability of these processes in an interval of time dt is represented as:

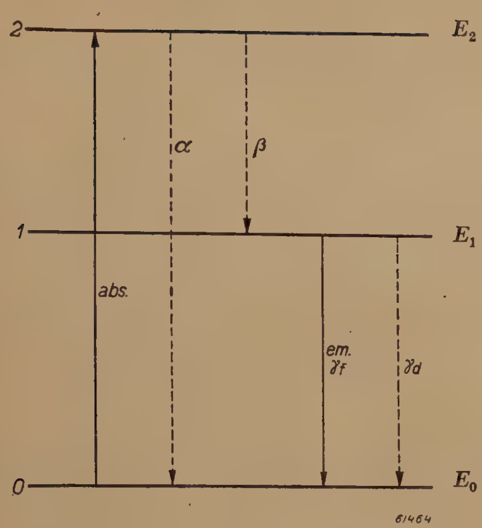


Fig. 9. System with two excited states (*1* and *2*), indicating the transition through absorption to state *2*, the transition *1* → *0* under emission, and various radiation-less transitions (in dotted lines).

	with radiation	without radiation
2→*0*	α_f dt	α_d dt
2→*1*	β_f dt	β_d dt
1→*0*	γ_f dt	γ_d dt

In many cases no radiations are found corresponding to α_f and β_f, or in other words α_f and β_f are zero, or at least $\alpha_d \gg \alpha_f$, $\beta_d \gg \beta_f$. In the simplified assumption that this is the case, we find for the efficiency of the fluorescence (transition *1* → *0*):

$$\eta = \frac{\beta_d}{\alpha_d + \beta_d} \cdot \frac{\gamma_f}{\gamma_f + \gamma_d} \cdot \quad . \quad . \quad . \quad (10)$$

If, as is often the case, γ_f is small compared with α_d and β_d, it may easily be deduced that α_d and β_d have no effect upon the decay of the fluorescence after interruption of the irradiation but that an increase of γ_d accelerates that decay. If with such systems there is found to be a decrease in efficiency then this opens the possibility of investigating at what level the interfering radiation-less process takes place: if it is found that with increasing quenching (decreasing value of η) there is at the same time a decrease in the duration of the decay then the quenching is caused by γ_d; if that is not the case then the cause lies in the ratio of α_d/β_d. Examples of both cases have been found experimentally. Systems are also known where both effects take place simultaneously.

From formula (10) it appears that the efficiency is determined not only by the ratio γ_d/γ_f but also by that of α_d to β_d. If α_d and β_d increase differently with the temperature it is quite possible that at first, before the influence of γ_d is noticeable, the efficiency increases with rising temperature. This possibility has already been pointed out in the introduction.

The foregoing also applies in the case where state *2* does not belong to the centre as such but represents an excited state of the crystal lattice. This means that then an electron travels through the lattice, just as is the case with the positive charge (electron "hole") that is left after the electron is removed from a lattice ion (see, e.g., the article quoted in footnote [2]). For the transition from state *2* to state *1* it is now necessary that the electron and the positive charge meet near a centre, a part $E_1 - E_0$ of the energy $E_2 - E_0$ being thereby transmitted to the centre, while the remainder $(E_2 - E_1)$ goes to the lattice. The number of such transitions per unit of time is proportional to the product of the concentrations of excited electrons and the holes, thus proportional to the square of the number n_2 of electrons in the state *2*, contrary to the cases considered above, where the number of transitions was invariably proportional to the first power of the number of electrons in the respective state. The most important consequence of this is that, if such a "bimolecular" process governs the variation of the fluorescence as function of time during the decay, this variation is no longer exponential but "hyperbolic", which means to say that for high values of t the intensity decreases proportionally [9]) with $1/t^2$.

If in this case, in addition to the transition leading to fluorescence, there is a quenching process, likewise governed by a "bimolecular" process (recombination of electrons and holes), then we find again for the efficiency an expression of the form:

$$\eta = \frac{\beta}{\alpha + \beta} \cdot \frac{\gamma_f}{\gamma_f + \gamma_d} \cdot$$

Here β is the coefficient determining the transition from the state *2* to state *1* and α a similar coefficient for the extinction process *2* → *0*.

Still more complicated is the case where the radiation-less transition from *2* to *1* is indeed "bimolecular", i.e. proportional to n_2^2, but the competing process, the radiation-less transition *2* → *0*, is "monomolecular", i.e. proportional to the first power of n_2. Obviously the counteraction between these processes then depends upon the value of n_2. In such a case the efficiency will be found to be dependent upon the intensity of the irradiation.

Such a behaviour has indeed been found with willemite (Zn_2SiO_4—Mn_2SiO_4) containing a relatively-large amount of manganese: a preparation containing,

[9]) Cf. Philips Techn. Rev. 3, 241-247, 1938 (especially pp 246 and 247).

say, 5% manganese can be made to fluoresce by irradiating it with a wavelength of 3650 Å, this wavelength being selectively absorbed by the Mn-ions. The decay of the fluorescence after the irradiation has ceased is exponential with time, the decrease in efficiency with rising temperature beginning at the same point where also the decay begins to decrease. Just as has been explained for the case of the uranyl salt, here too γ_f and γ_d can be determined ($S = 8.7 \times 10^9$, $\varepsilon = 0.89$ eV). When, however, the system is irradiated with $\gamma = 2537$ Å, coming within the range of lattice absorption, the behaviour of the decay remains the same but the efficiency begins to decrease at lower temperatures, the more so as the intensity of the irradiation is less (*fig. 10*). Something similar is found in the case of willemite containing, in addition to say 1% Mn_2SiO_4, a very small quantity (0.1%) of Fe_2SiO_4, the Fe-ions acting as quenchers.

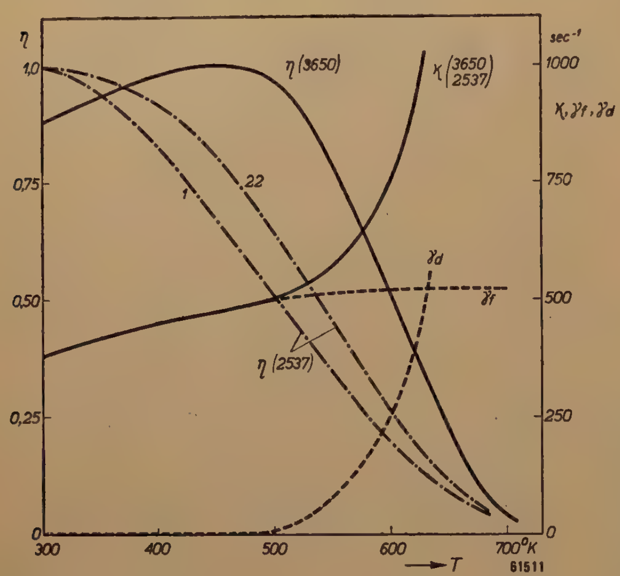


Fig. 10. The efficiency η and the quantities $\varkappa$, γ_f and γ_d for willemite with 5% Mn as function of the temperature T under irradiation with $\gamma = 3650$ Å and $\gamma = 2537$ Å, in the latter case for two intensities in the ratio 1 : 22.

These brief indications of such more complicated cases have to suffice here. For a more detailed treatment of the subject reference is made to the original publications dealing with the investigations [10]).

[10]) F. A. Kröger, W. Hoogenstraaten, M. Bottema and Th. P. J. Botden, The influence of temperature quenching on the decay of fluorescence, Physica **14**, 80-96, 1948.
F. A. Kröger and W. Hoogenstraaten, Decay and quenching of fluorescence in willemite, Physica **14**, 425-441, 1948.
W. Hoogenstraaten and F. A. Kröger, The intensity-dependence of the efficiency of fluorescence of willemite phosphors, Physica **25**, 541-556, 1949 (No. 5/6). For older literature, dealing especially with the fluorescence of gases and liquids, see P. Pringsheim, Fluorescence and Phosphorescence, Interscience P.C., New York, 1949.

Summary. It is explained how the efficiency of the fluorescence of all kinds of substances is influenced by dissipative processes tending towards quenching of the fluorescence. First a simple case is taken to show the relation that must exist between the increasing quenching with rising temperature and the simultaneous decrease of the decay time. Methods are briefly discussed for measuring the efficiency and the duration of the decay, and the results of the measurements for simple cases are compared with the theory. Finally mention is made of the complications arising in less simple cases and examples are given of cases where the efficiency depends not only upon the temperature but also upon the intensity of the irradiation.

A MEASURING ARRANGEMENT FOR WAVEGUIDES

by A. E. PANNENBORG.

621.392.26: 621.317.3

In installations for generating and receiving microwaves the super- and ultra-high-frequency energy is carried by waveguides. The construction of such waveguide systems and the accessory apparatus has to meet demands quite different from those required of transmitting and receiving installations for longer waves. Special measuring arrangements are needed to ascertain whether these demands are satisfied.

Introduction

The spectrum of electromagnetic oscillations can be divided into two parts. To the first part, which we shall call the optical range, belong all oscillations having a wavelength less than 0.01 mm, whilst in the second part, the electrical range, lie the oscillations with wavelengths greater than approximately 1 mm. Oscillations with intermediate wavelengths play no part so far in practical applications. (The limits mentioned here cannot be sharply defined and are to be regarded only as indicating the order of size.) The short-wave end of the electrical range, the so-called microwave range, with wavelengths between 1 mm and about 30 cm, can in a certain sense be regarded as a transitional range, and it is this part of the spectrum with which we shall deal in this article.

The last decade has seen great progress in the development of microwave technique; its application in radar and other related apparatus has become generally known. Since the wavelength of microwaves is comparable to the dimensions of normal circuit elements (capacitors, coils, etc.) such as are commonly used for longer waves, these elements can no longer be employed in a radar installation and we have to use elements of an entirely different nature. Neither is it possible for the microwave energy to be transported via a normal parallel-wire transmission line, because the losses due to radiation would then be prohibitive, so that either coaxial cables or waveguides have to be used. The theory of the propagation of electromagnetic waves through such systems is well known. It appears that a coaxial cable can transport microwave energy in a suitable manner only when half the sum of the circumferences of the inner and outer conductors is less than the wavelength of the oscillation. For wavelengths exceeding 10 cm the coaxial cable is highly suitable, but for smaller wavelengths when, as in radar installations, the power to be transported is, moreover, considerable (sometimes even amounting to several megawatts peak) it is advantageous to use waveguides. These have a much greater power-carrying capacity than the small coaxial cables required for centimetric waves, without sparking occurring in the guide, and moreover in this range they have reasonable cross-sectional dimensions, of the order of the wavelength of the oscillation.

When waveguides are used as transmission lines all sorts of problems are encountered. To mention some of them: there is the manner in which the energy has to be fed into the waveguide at one end and taken off at the other end, the effect of bends and junctions, the way in which the electromagnetic field is influenced by obstacles in the guide, the matching of the various parts of a waveguide system, and so on. In order to illustrate the great importance of these problems in practice, a diagram (*fig. 1*) is given, representing the high-frequen-

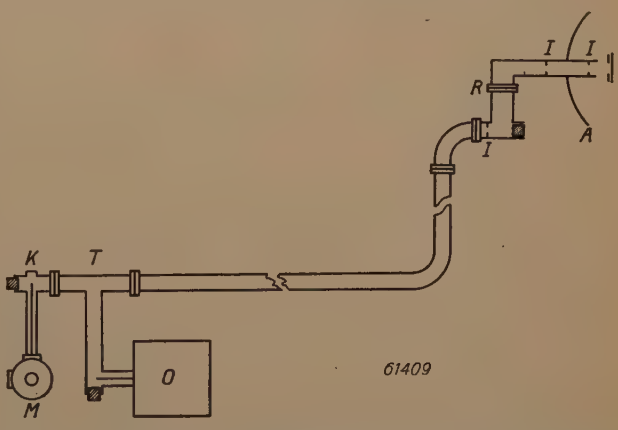


Fig. 1. Lay-out of the high-frequency part of a radar installation. The oscillations generated by the magnetron M are conducted by a coaxial cable and a coupling K to the waveguide, which carries them to the aerial A, where they are radiated into space. This aerial serves at the same time for receiving the reflected signals, for instance from an aeroplane, which pass along the same waveguide to the receiver O, connected to the waveguide via a branch T. The aerial is rotated with the aid of a rotating joint R. To allow for correct matching some diaphragms I occupy part of the cross section of the waveguide. (From Principles of Radar, M.I.T. Radar School Staff, McCraw Hill Book Cy, New York 1946.)

cy part of a radar installation, clearly showing the bends, couplings, etc. occurring in it.

For investigating the properties of these obstacles, bends, etc. it is necessary to take certain measurements. Measurements of the reflections are particularly important, because, as we shall see presently, in a waveguide reflections generally have to be avoided. It is these measurements that will be dealt with in this article; naturally only a limited part of the vast measuring technique can be discussed and for a more intensive study the reader is referred to the extensive literature already published on this subject [1]).

Before proceeding to describe the technique of measuring we have to give a brief review of the essential theory of waveguides. This theory has already been dealt with more extensively in two articles previously published in this journal [2]).

Propagation of waves in waveguides

Here we shall confine ourselves to rectangular waveguides with sides a and b, where $b < a$. As described in article I, in such a waveguide modes of different types may occur. There are transverse electric modes of various orders (TE_{mn} modes) and transverse magnetic modes of various orders (TM_{mn} modes). It appears that a TE_{mn} mode (we are dealing here only with TE modes) can be propagated through the guide only when the following relation between the wavelength λ and the dimensions of the guide is satisfied:

$$\frac{1}{\lambda} > \frac{1}{\lambda_{cr}} = \sqrt{\left(\frac{m}{2a}\right)^2 + \left(\frac{n}{2b}\right)^2}; \quad . \; . \quad (1)$$

λ_{cr} is called the critical wavelength for the TE_{mn} mode.

From formula (1) it immediately follows that the greatest critical wavelength is given by $\lambda_{cr} = 2a$, belonging to a TE_{10} mode, whilst the next greatest critical wavelengths are given by $\lambda_{cr} = 2b$ (TE_{01} mode) and $\lambda_{cr} = a$ (TE_{20} mode).

It is desirable that the waves should be propagated in a guide in a single mode, since the reflecting properties of a discontinuity differ for each mode of oscillation. The guide is therefore given such dimensions that the mode of oscillation lies between the greatest and the next greatest critical wavelength, i.e. so that only TE_{10} waves can be propagated in the guide. The bandwidth available is made as large as possible by choosing $b < {}^1/_2\, a$; it is then determined by the length of the wide side a; all microwaves having a wavelength satisfying the inequality $a < \lambda < 2a$ can then be propagated through the guide as a TE_{10} mode.

Waves with a greater wavelength cannot penetrate into the guide, because as soon as they enter it they change into a stationary wave (perpendicular to the axis) the amplitude of which diminishes exponentially along the axis of the guide. There is also some attenuation in the case of the propagation of waves within the permissible frequency band, owing to the dissipative losses caused by the current flowing along the surface of the guide; the closer the wavelength lies to the greatest critical wavelength, the greater is the attenuation. In practice, therefore, only the wavelength range $a < \lambda < 1.6a$ can be used. See also article I, pp 24 and 25.

The formulae describing the electromagnetic field of a TE_{10} mode in a rectangular waveguide are (see I, p. 23 and 24):

$$E_y = A \sin\frac{\pi x}{a}\, e^{2\pi j\varphi},$$

$$H_x = A \sqrt{\frac{\varepsilon_0}{\mu_0}} \sqrt{1-\left(\frac{\lambda}{2a}\right)^2}\, \sin\frac{\pi x}{a}\, e^{2\pi j\varphi},$$

$$H_z = A \sqrt{\frac{\varepsilon_0}{\mu_0}}\, \frac{\lambda}{2a} \cos\frac{\pi x}{a}\, e^{2\pi j(\varphi - {}^1/_4)},$$

$$E_x = E_z = H_y = 0,$$

where

$$\varphi = \frac{c}{\lambda}\left\{t - \frac{z}{c}\sqrt{1-\left(\frac{\lambda}{2a}\right)^2}\right\}.$$

In these formulae ε_0 and μ_0 represent respectively the dielectric constant and the magnetic permea-

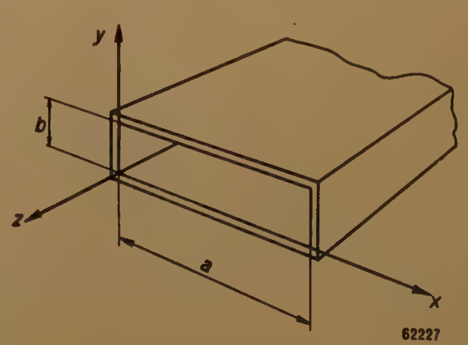


Fig. 2. Sketch of a rectangular waveguide with sides a and b ($a > b$). The system of coordinates indicated in the sketch is that used for the calculations in this article.

[1]) See, e.g., C. G. Montgomery, Technique of microwave measurements, Radiation Laboratory Series **11**, McGraw Hill Book Cy, New York, 1947, and J. G. H. Huxley, A survey of the principles and practice of wave guides, Cambridge University Press, 1947.

[2]) W. Opechowski, Electromagnetic waves in wave guides, I, Philips Techn. Rev. **10**, 13-25, 1948, and II, Philips Techn. Rev. **10**, 46-54, 1948. From now on these articles will be referred to as I and II respectively.

bility of the vacuum, λ represents the wavelength in vacuo, c the velocity of light and A an arbitrary constant.

The system of coordinates has been so chosen that the z-axis is parallel to the longitudinal direction of the wave guide, the x-axis parallel to the side a and the y-axis parallel to the side b of the cross section (*fig. 2*).

From the above formulae it is seen that the z-dependency of the mode is given by the factor $\exp\left(-2\pi jz\sqrt{1/\lambda^2-(1/2a)^2}\right)$. This means that the wavelength λ_z at which the oscillation is propagated in the waveguide is not equal to λ but is given by the formula

$$\frac{1}{\lambda_z}=\sqrt{\frac{1}{\lambda^2}-\frac{1}{(2a)^2}}. \quad \dots\dots \quad (2)$$

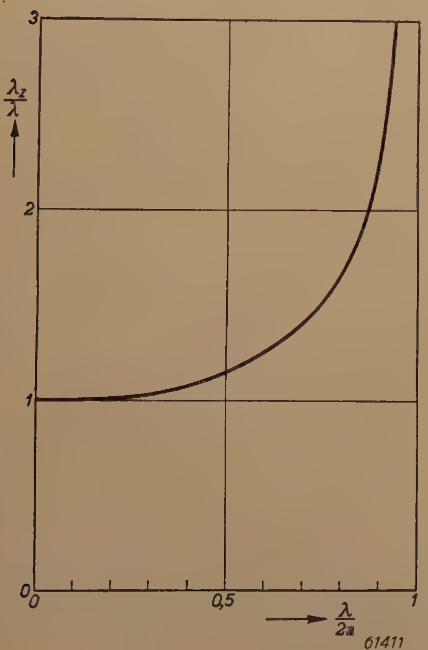


Fig. 3. The wavelength λ_z of an oscillation propagated in a waveguide of the width a, divided by the wavelength λ of the oscillations as produced by the generator, plotted as a function of the ratio $\lambda/2a$. It appears that λ_z may easily be twice as great as λ.

In *fig. 3* λ_z/λ has been plotted as a function of $\lambda/2a$. It is seen that λ_z can easily be twice as great as λ.

Fig. 4a shows the magnetic lines of force for the case of a TE_{10} wave in a rectangular waveguide; here the significance of λ_z is made quite clear. In this diagram the electric lines of force are at right angles to the plane of drawing, the intensity of the electrical field varying across the width of the waveguide as indicated in fig. 4*b*. Finally the system of currents flowing along the surface of the waveguide is represented in fig. 4*c*.

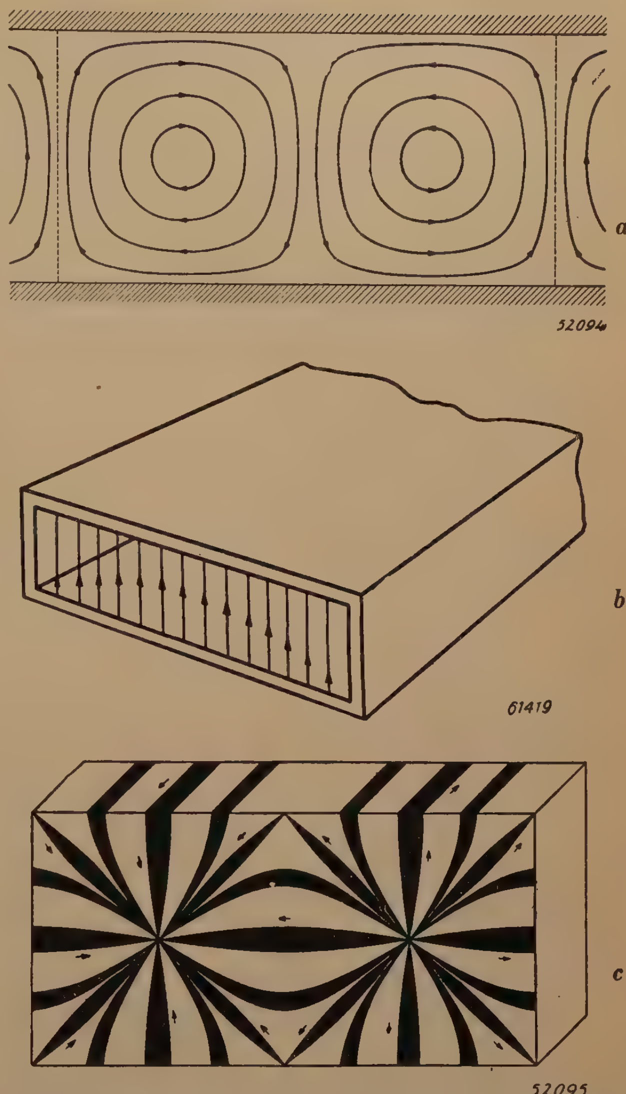


Fig. 4. *a*) Magnetic lines of force for a TE_{10} mode in a rectangular waveguide. This figure represents an "instantaneous photograph" of a cross section parallel to the wide sides, and thus also parallel to the direction of propagation of the wave. The wavelength at which the oscillation travels through the guide, λ_z, is equal to the distance between the two dotted vertical lines.
b) Electric field strength for a TE_{10} mode in a rectangular waveguide. The lines of force are all at right angles to the wide side.
c) Density distribution of the surface currents on the walls of a rectangular waveguide in which a TE_{10} mode is propagated. The width of the lines of current is proportional to the current density ("instantaneous photograph").

The occurrence of standing waves

When there is a discontinuity in a waveguide, for instance in the form of a sudden narrowing, then the wave will be reflected. The same may be the case at the end of the waveguide, for instance where it is coupled to the aerial, or where there is a bend in the guide.

In order to get an idea of the effect of such discontinuities we can avail ourselves of the similarity that exists between a waveguide in which, for instance, only the TE_{10} mode can be propagated,

and a transmission line. In the theory of transmission lines voltage and current are regarded as the fundamental quantities. In the case of a waveguide these quantities can no longer be unambiguously defined. One can, however, speak of reflections both in transmission lines and in waveguides. As a rule reflections occur in a transmission line when it is terminated with an impedance. The effect of a load impedance Z on the currents and voltages in a transmission line can be deduced as follows[3]).

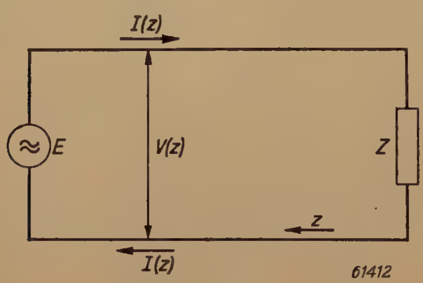


Fig. 5. Transmission line, with a load impedance Z, connected to the high-frequency voltage source E. At a distance z from the right-hand end the voltage and current are respectively $V(z)$ and $I(z)$.

As is known, the current and voltage at a certain point z in a transmission line (*fig. 5*) can be described by:

$$V(z) = \left\{A e^{+j\gamma z} + B e^{-j\gamma z}\right\} e^{j\omega t},$$

$$I(z) = \left\{\frac{A}{\zeta} e^{+j\gamma z} - \frac{B}{\zeta} e^{-j\gamma z}\right\} e^{j\omega t},$$

where A and B are constants independent of z and t; γ is called the propagation constant. The quantity ζ is called the characteristic impedance of the system.

In the following we shall omit the time factor $e^{j\omega t}$, as not being essential for our considerations.

At the terminating impedance Z ($z = 0$) we have

$$V(0) = A + B \text{ and } I(0) = \frac{A}{\zeta} - \frac{B}{\zeta},$$

and therefore

$$Z = \frac{V(0)}{I(0)} = \frac{A+B}{A-B}\zeta . \quad \dots \dots \quad (3)$$

Hence

$$\frac{B}{A} = \frac{Z-\zeta}{Z+\zeta} = f, \quad \dots \dots \quad (4)$$

and for the variation of the voltage we get

$$V(z) = A\left\{e^{+j\gamma z} + \frac{Z-\zeta}{Z+\zeta} e^{-j\gamma z}\right\} = A\left\{e^{+j\gamma z} + f e^{-j\gamma z}\right\}. \quad \dots \quad (5)$$

The first term between brackets in this formula can be regarded as a wave travelling to the right and the second term as a wave travelling to the left, imagined as arising from reflection of the former wave at the impedance Z. The degree of reflection is determined by the equation

$$f = \frac{\frac{Z}{\zeta} - 1}{\frac{Z}{\zeta} + 1}, \quad \dots \dots \dots \quad (6)$$

f being called the reflection coefficient, which is usually a complex quantity.

Owing to superposition of the waves travelling to the right and to the left, standing waves occur. At distances of a quarter of a wavelength there are voltage maxima alternating with voltage minima. These maxima and minima are given by the extreme values of (5) and are respectively

$$V_{\max} = |A|\left\{1 + |f|\right\} \text{ and}$$

$$V_{\min} = |A|\left\{1 - |f|\right\},$$

so that the ratio of the minimum to the maximum voltage, which indicates to what extent the resulting wave bears the character of a standing wave, is determined by the quantity

$$r = \frac{1-|f|}{1+|f|}. \quad \dots \dots \dots \quad (7)$$

r is called the voltage standing-wave ratio (V.S.W.R.) for the impedance Z. By measuring the V.S.W.R., which can easily be done (see the article quoted in footnote [3])), the absolute value of the reflection factor can be determined. The argument of f, which is a measure of the phase shift resulting from the reflection, can be found from the distance between the point where the impedance Z is connected to the transmission line and the first voltage minimum, as already described in the article of footnote [3]).

Let us now revert to the rectangular waveguide. A discontinuity in the guide will result in a very complex wave pattern in its immediate vicinity, a pattern which can be regarded as a superposition of all the infinite number of modes of oscillation of the guide. Since only the TE_{10} waves are able to travel through the guide with small attenuation, at some distance in front of the discontinuity we shall find only the original wave and a reflected

[3]) See J. M. v. Hofweegen, Impedance measurements with a non-tuned Lecher system, Philips Techn. Rev. 8, 278-286, 1946.

wave. The superposition of these two waves again gives rise to standing waves. In analogy with the foregoing we can now introduce a reflection coefficient f, viz. the ratio of the amplitudes of the reflected and the original wave. Whereas in the case of the transmission line we had the ratio of two voltages to consider, here we have to reckon with the ratio of two electric fields, for instance the electrical field strengths of the waves in the forward and return directions.

ring will already be 25% less than that when the guide is matched ($r = 1$).

A description will now be given of an arrangement used in the Philips Laboratories at Eindhoven for measuring the V.S.W.R.

Measuring the V.S.W.R.

When it is desired to match one element of a waveguide to another, for instance when the aerial of a radar system is to be coupled as efficiently

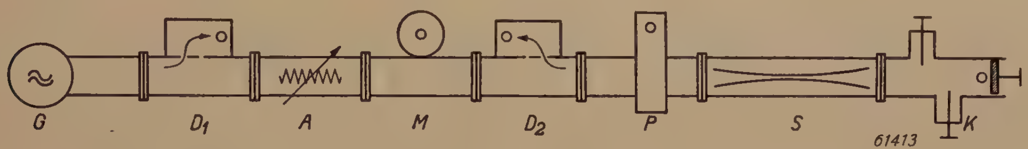


Fig. 6. Diagram of the lay-out for measuring voltage standing-wave ratios. G generator of the microwaves, D_1 and D_2 directional couplers, A attenuator, S slotted waveguide along which a probe (not shown) can be shifted, P fixed probe, M wavemeter, K detector which can be tuned and the voltage standing-wave ratio of which is to be measured. The small circles in the directional couplers and in the probe P represent crystal detectors with their matching elements.

In the case of transmission lines we found a reflection due to the presence of an impedance differing from the characteristic impedance ζ. With waveguides, too, an impedance can be ascribed to the discontinuity, by writing in analogy with (6):

$$f = \frac{\frac{Z}{\zeta} - 1}{\frac{Z}{\zeta} + 1}.$$

Just as current and voltage cannot be unambiguously determined, neither can the charateristic impedance ζ of a waveguide, except as the ratio Z/ζ in equation (6).

The magnitude of a standing wave in the waveguide can be expressed by the ratio of the minimum to the maximum amplitudes in the guide, thus by the voltage standing-wave ratio r, which, in analogy with (7), is related to $|f|$ according to the equation

$$r = \frac{1 - |f|}{1 + |f|}.$$

Under reflectionless conditions we find $f = 0$, thus $r = 1$, whilst for a perfectly reflecting termination $|f| = 1$, thus $r = 0$.

It is of great importance to keep the V.S.W.R. in a system as small as possible. When reflections occur, as for instance in a radar installation, these will react upon the oscillating magnetron and possibly disturb its stability. Moreover, although with a V.S.W.R. of say 0.6 the energy reflection from a discontinuity is still very small (about 6% = 0.5 db), the maximum power that can be sent through the guide without sparking occur-

as possible, it is necessary to measure the V.S.W.R. occurring as a result of reflection from that element, and to minimize this reflection. The latter can be done, for instance, by purposely introducing an obstacle, say an adjustable screw, which by its own reflections just neutralizes the reflections originally present. To confine our thoughts let us suppose that a detector has to be matched to a microwave installation in order to measure the strength of the signal in the waveguide. For this purpose we employ an arrangement as represented diagrammatically in *fig. 6.* The generator G produces a signal which is conducted along a number of parts, which will be described below, and finally reaches the detector K. There, as a rule, part of the signal will be reflected, with the result that standing waves arise in the whole of the guide. Placed in front of the detector is the "V.S.W.R. meter" S, consisting, for instance, of a short section of a waveguide in which the field can be scanned with a probe. This probe, not shown in the drawing, extracts a small part of the energy in the guide and passes it on to a measuring instrument connected to the probe. The voltage induced at the probe is proportional to the electric field at that point, so that by moving the probe along the guide it is possible to measure the voltage minimum and maximum due to the occurrence of the standing wave, and the ratio of these two voltages gives the V.S.W.R.

The probe can be made in the following way. First a slot is cut in the longitudinal direction of the waveguide down the centre of the long side;

this scarcely disturbs the system of surface currents, and thus the field, as may be seen from fig. 4*c*. Through this slot a thin wire can then be inserted a very short way into the guide (see *fig.* 7). This

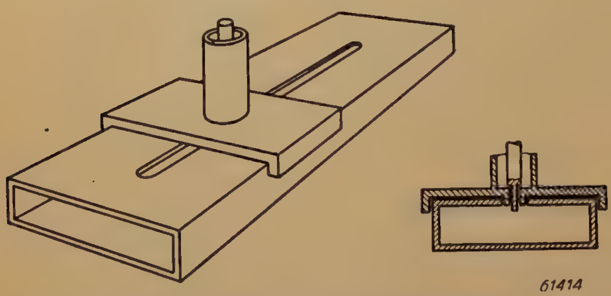


Fig. 7. Sketch of a probe that can be moved along the waveguide.

probe is then parallel to the electric lines of force and thus measures the electric field at the point where it is situated. The shorter the distance that the probe penetrates into the guide the less is the disturbance of the field, and it can usually be ignored. The probe is mounted on a carriage made to slide along the guide, care being taken to ensure that the probe is well centred in the slot and kept at the same depth of penetration into the guide. The latter requirement is not so easy to fulfil and a simpler method is therefore often applied, where a permanently fixed probe (*P* in fig. 6) and a waveguide of variable width are employed.

As we have already seen, an oscillation is propagated along the guide with a wavelength λ_z depending upon the width *a* of the guide (see formula (2) and fig. 3). This wavelength can therefore be varied by "squeezing" the guide and thus it is possible to change the number of wavelengths between the section of which the V.S.W.R. is to be measured and the fixed probe. This variation of the "electrical length" corresponds to a displacement of the field along the probe, so that by squeezing the guide, in which there is somewhere a fixed probe, we achieve the same object as when moving the probe along the field inside the guide in the manner described above.

A so-called squeeze section can be obtained by cutting a longitudinal slot down the centre of the two wide sides and placing midway over it a clamp with which the guide can be constricted a few millimetres. In *fig. 8* two types of a squeeze section are shown, one for 3 cm waves and the other for 10 cm waves. The guide for 10 cm waves is fitted with a dial gauge for measuring the constriction of the squeeze section.

It is advantageous to squeeze the guide periodically. In the Philips Laboratories a method is employed whereby the guide is squeezed once in about every two seconds by means of two cams driven by an electromotor. The voltage on the probe will vary in rhythm with the constrictions, and the ratio of the lowest to the highest voltage indicated by a meter which has little inertia is a measure for the V.S.W.R.

Here the "probe" does not consist of a wire but is formed by a so-called window communicating between the main guide and a section of waveguide mounted on it crosswise and containing a detector. After amplification the voltage supplied by the detector can be measured; we shall revert to this later on.

A V.S.W.R. meter such as described here is only suitable for measuring small standing-wave ratios. It often happens that the matching of a variable waveguide section is at first so bad that the V.S.W.R. has a very high value. For quickly matching the section in such a case it is advisable

Fig. 8. Two types of a squeeze section . The large section (for 10 cm waves) is fitted with a dial gauge for calibrating the electrical length of the waveguide as a function of the width of the slit.

to have available a coarser indicator of the V.S.W.R. This is to be found in what is called the directional coupler, by means of which the strength of the reflected signal can be measured. A directional coupler consists of a branch waveguide connected to the main waveguide by windows and in which a wave is propagated which is a certain fraction of a wave travelling in one direction along the main waveguide. A diagrammatic representation of such a directional coupler is given in *fig. 9* [4]). The

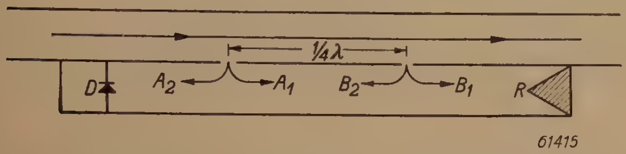


Fig. 9. Basic principle of a directional coupler. The two windows in the common, narrow wall of the waveguides are spaced at a distance of $^1/_4\ \lambda_z$. A wave travelling to the right sets up through each window a secondary wave travelling to the left and to the right. The wave B_2 follows a path half a wavelength longer than that of the wave A_2. Thus the two waves neutralize each other. A_1 and B_1 on the other hand reinforce each other, so that in the secondary waveguide there is exclusively a wave travelling to the right. Similarly, a wave travelling to the left in the main waveguide will give rise exclusively to a wave travelling to the left in the secondary guide. The wave travelling to the right can be absorbed by a non-reflecting termination R. Thus the detector D receives only a signal from the wave travelling to the left in the main waveguide.

two identical windows in the common, narrow, side wall of the two waveguides are spaced a quarter of a wavelength apart ($^1/_4\ \lambda_z$). A wave travelling to the right through the main guide gives rise to a secondary wave passing through each of the windows into the secondary guide and travelling to the right and to the left. The waves A_1 and B_1 reinforce each other; the waves A_2 and B_2 however neutralize each other through interference, since the wave B_2 follows a path half a wavelength longer than that followed by the wave A_2. For proper neutralizing of the waves A_2 and B_2 it is necessary that the coupling should be weak, or in other words: the attenuation of the wave in the main guide caused by a window must be negligible, so that this wave can pass both the windows with the same strength and thus the waves A_2 and B_2 formed in the secondary guide are of the same intensity.

In this way a wave travelling to the right in the main guide results exclusively in a wave travelling to the right in the secondary guide; similarly, a wave travelling to the left in the main guide produces in the secondary guide exclusively a wave travelling to the left. The right-hand end of the secondary guide can now be closed with a non-reflecting termination (for instance with a wedge of dissipative material) and on the left-hand end of the guide a detector can be mounted.

This detector will then pick up only a signal from the wave travelling towards the left in the main guide and a wave travelling to the right in this guide will not reach the detector. In this way it is therefore possible to detect at once the presence of a reflected wave.

What it amounts to in practice is that, measuring with the directional coupler, we can make the matching of a waveguide section such that the V.S.W.R. for that element exceeds 0.95, which corresponds to an energy reflection of 0.06%. Measuring with the squeeze section we can then carry out the accurate adjustment, since it is possible to measure a V.S.W.R. of 0.99, corresponding to an energy reflection of only 0.0025%.

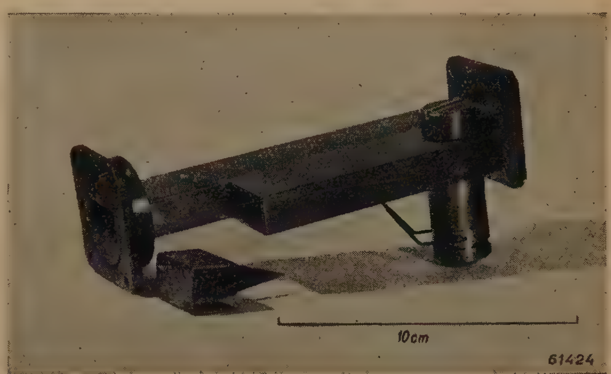


Fig. 10. Photograph of a directional coupler for a 3 cm waveguide. The wedge acting as a matched termination of one of the ends has been removed from the secondary waveguide.

A photograph of a directional coupler for a 3 cm waveguide is given in *fig. 10*. By way of illustration the wedge for the non-reflecting termination of the section is shown beside the coupler.

Fig. 11 is a photograph taken of the whole of the set-up described here.

Accessories for the measuring device

We shall now describe a few accessories (some of which have already been mentioned) which may be useful for a measuring device as described.

A generator is needed for generating the microwaves used in carrying out the measurements. For this one usually employs a velocity-modulation valve (reflex klystron), which is capable of supplying a power of some milliwatts up to some tens of milliwatts. This valve oscillates only when the value of the reflector voltage lies within certain

[4]) See K. S. Knol and G. Diemer, A model for studying electromagnetic waves in rectangular wave guides, Philips Techn. Rev. 11, 156-163, 1949 (No. 5).

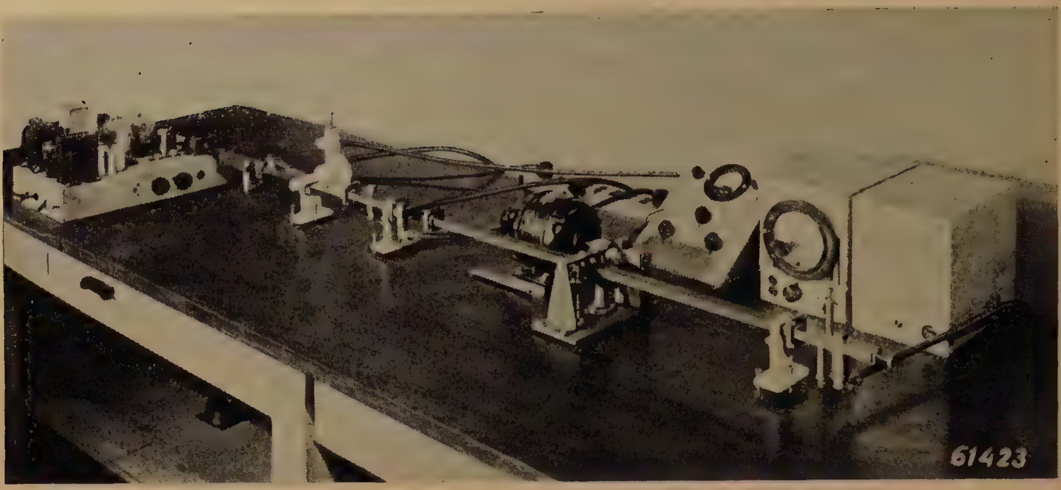


Fig. 11. Photograph of the complete device for measuring standing waves, as employed in the Philips Laboratories.

ranges. The frequency of the energy generated can be varied over a band width of about 10% by mechanical tuning of the cavity resonator of the valve, and further over a more limited range by varying the reflector voltage within an oscillating range. For our measurements an A.F. amplitude modulation of the signal is desired. The voltage picked up by the fixed probe in the squeeze section can then be amplified, after detection, with the aid of an A.F. amplifier. Although the amplitude of the oscillations greatly depends upon the reflector voltage, the method of modulating the amplitude of the signal by sinusoidally varying this voltage is not suitable, because then frequency modulation occurs at the same time. It is possible, however, to get a pure amplitude modulation by applying to the reflector square waves of such an amplitude that the valve is alternately oscillating and not oscillating. This is the method employed with the measuring device described here.

The microwaves are conducted from the oscillator to the waveguide via a short coaxial cable (*fig. 12*). At one end of this cable the inner conductor is bent into a small loop, which is connected to the outer conductor, and this loop is inserted in the cavity resonator of the reflex klystron. At the other end of the cable the inner conductor is extended into the wave guide parallel to the electric lines of force, like an aerial, whilst the outer conductor is connected to the wall of the waveguide. The guide is closed at one end with a piston, in such a way that maximum power is obtained in the desired direction.

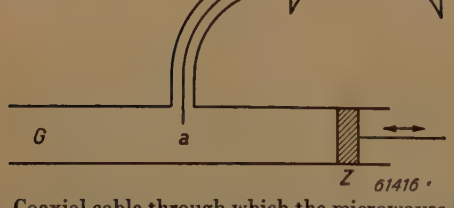


Fig. 12. Coaxial cable through which the microwaves generated by the reflex klystron are conducted to the waveguide. The small loop *l*, inserted in the cavity resonator of the valve, takes up the energy; the "aerial" *a* is the inner conductor of the coaxial cable extending into the waveguide *G* parallel to the electric lines of force. Here the measuring apparatus is to the left of the aerial; the waveguide, however, has been extended somewhat to the right to allow of the terminating of the guide at that end with a piston *Z* which can be adjusted so that the maximum energy is obtained in the desired direction.

As the first element behind the generator there is usually a variable strip attenuator, by means of which the signal amplitude can be adjusted while at the same time the generator is decoupled from the system; in the case of quantitative measurements care has to be taken that the strength and the frequency of the signal are not affected by the generator load. The strip attenuator (*fig. 13*) is made in the form of a small sheet of dissipative material placed in the waveguide, the attenuation being brought about by eddy currents set up in the absorptive strip. Here again use is made of the possibility of cutting a longitudinal slot down the centre of the wide side of the guide without thereby disturbing the field inside the guide. The attenuation is controlled by the depth of penetration of the strip of dissipative material in the guide. The perimeter of the strip is rounded off so as to minimize reflections.

Mention has several times been made of a detector, which rectifies the H.F. voltages so as to be able to measure the energy. As such a detector a diode [5]) can still be used for waves of 10 cm and

[5]) M. J. O. Strutt and K. S. Knol, A diode for the measurement of voltages on decimetre waves, Philips Techn. Rev. 7, 124-128, 1942.

longer, but for shorter waves the diode is unsuitable on account of transit-time effects, and then a crystal detector has to be used. In principle a crystal detector does not differ from the crystals

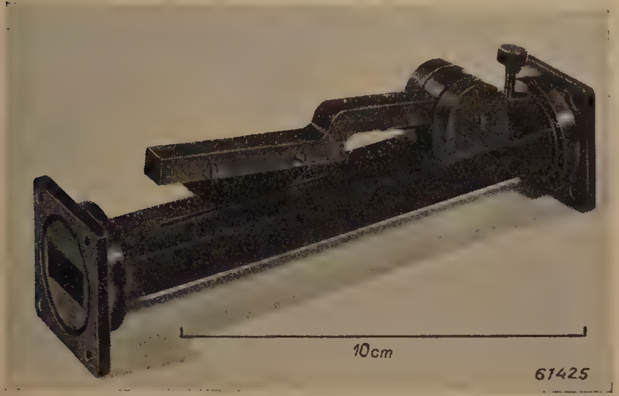


Fig. 13. Attenuator consisting of a small sheet of dissipative material which can be inserted in the waveguide through a longitudinal slot in the wide side.

that were formerly employed in radio engineering; recent investigations in America and England have made it possible to stabilize crystals, so that reliable and reproducible results can now be obtained. The crystal detector is highly suitable for microwaves owing to its small dimensions and small shunt capacitance.

The crystal is mounted in a cartridge (a ceramic tube with metal end caps) which is secured in a crystal holder consisting of a waveguide section of the same dimensions as the guide in which the power is to be measured (see *fig. 14*); the guide is terminated by a short-circuiting piston and fitted with some fixed or adjustable tuning elements, with which the matching can be so adjusted that all incident energy is absorbed in the crystal and thus no reflection takes place. The cartridge is placed with its longitudinal axis parallel to the electric field. The matching of a crystal holder has been taken as example in the description of the measuring of the V.S.W.R. in the preceding section of this article.

Another possible means of detection lies in the employment of elements the electrical resistance of which is dependent upon the temperature. Such an element forms part of a Wheatstone bridge circuit, with which the variation in resistance due to the heating of the element by the absorbed microwave energy is measured. Use can be made either of thin wires with a positive temperature coefficient of the resistance, or of semi-conductorss having a high negative temperature coefficient [6]) and usually of the "pin head" type enclosed in a glass envelope; the whole is placed in a holder with the leads running parallel to the high-frequency electric field. The advantage of such "bolometers" is that they can be directly calibrated with direct current and thus form direct wattmeters. On the other hand, however, they are less sensitive than crystal detectors.

The voltage supplied by the detector in the fixed probe used for measuring the V.S.W.R. is applied to the input of a linear selective amplifier, tuned to the frequency of the above-mentioned amplitude modulation with rectangular pulses of the oscillator signal. The output signal from the amplifier is rectified and passed to a meter provided with a scale giving direct readings of the V.S.W.R.

In addition to the directional coupler D_2, serving for the rough matching of waveguide sections with a large V.S.W.R., there is a second directional coupler (D_1 in fig. 6). This is coupled with the generator signal and serves for adjusting the generator output to the maximum with the aid of the voltages applied to the tube and further with the piston mentioned when dealing with the construction according to fig. 12.

Finally the system includes a frequency meter or wave meter for ascertaining the correct wavelength of the signal generated by the reflex klystron. The wavemeter contains, as resonating element, an adjustable cavity resonator or some other tuned system coupled to the waveguide. When the system is so tuned that resonance occurs at the frequency of the microwaves in the waveguide then the energy taken up in the system will be the maximum. There are two ways of determining this:

a) The tuning can be determined at which the

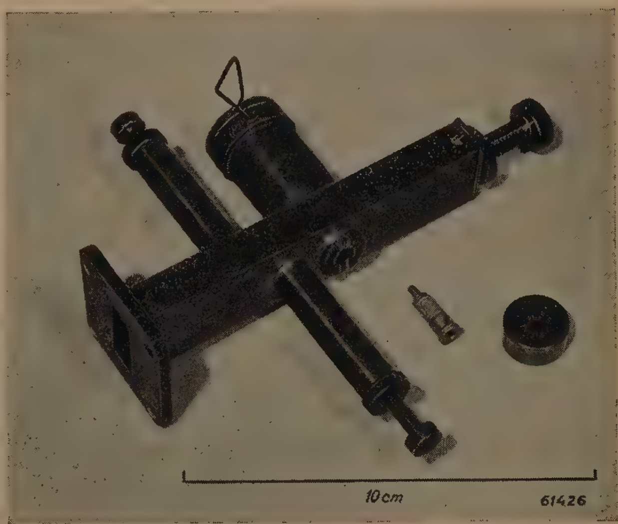


Fig. 14. Detector; the two lateral tubes fitted with a tuning screw are adjusting elements; the screw in the right-hand end of the waveguide serves for adjusting its terminating piston. The cartridge containing the crystal has been taken out of the detector.

[6]) See E. J. W. Verwey, P. W. Haayman and F. C. Romeyn, Semi-conductors with large negative temperature coefficient of resistance, Philips Techn. Rev. **9**, 239-248, 1947.

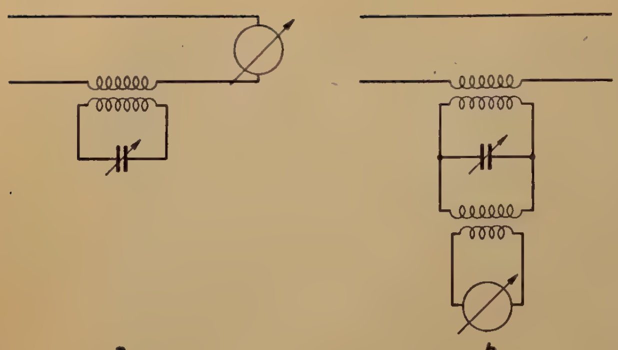


Fig. 15. Two methods for measuring the frequency of the microwaves with the aid of a wavemeter. *a*) Reaction-type wavemeter; the tuning is determined at which the energy loss in the waveguide due to absorption in the resonating wavemeter reaches the maximum. *b*) Transmission-type wavemeter; the tuning is determined at which the energy transmitted by the resonating system to the meter reaches the maximum.

loss in power suffered by the wave travelling in the waveguide as a result of the presence of the wavemeter reaches the maximum; for instance by measuring the voltage induced in the fixed probe of the V.S.W.R. meter (in the case of constant width of the waveguide) as a function of the adjustment of the wavemeter. When this voltage is the minimum the wavemeter resonates and from its adjustment one can determine the frequency (reaction-type wavemeter).

b) It can be directly determined when the power taken up by the wavemeter is greatest, with the aid of a detector and a voltmeter connected to the wavemeter (transmission-type wavemeter; the power measured is now the the maximum when resonance occurs).

These two methods of measuring are represented diagrammatically in *figs. 15a* and *15b*.

It depends upon the wavelength of the microwaves what kind of tuned system is used. For 3 cm waves an adjustable cavity resonator is mostly used (*fig. 16a*); one of the end plates of this resonator is adjustable with a micrometer screw.

Fig. 16. *a*) Wavemeter in the form of a variable cavity resonator for 3 cm waves. One of the end plates can be moved with a micrometer screw. *b*) Wavemeter for 10 cm waves; this is in the form of a transmission line which can be tuned. Both wavemeters are coupled to the waveguide by means of windows.

For longer waves (10 cm) usually a tuned coaxial transmission line is employed (fig. 16*b* and, diagrammatically, *fig. 17*). At resonance the inner conductor is $^3/_4$ wavelength long; the sliding contact on the rod is $^1/_4$ wavelength distant from the shortcircuited end, for the average frequency for which the meter is suitable, so that it always lies near a current node and the contact does not have to answer stringent requirements.

The coupling with the waveguide is usually brought about by mounting the cavity resonator or transmission line direct on the waveguide and allowing the electromagnetic field to enter the wavemeter via a window, as is to be seen in figs. 16*a*, 16*b* and 17.

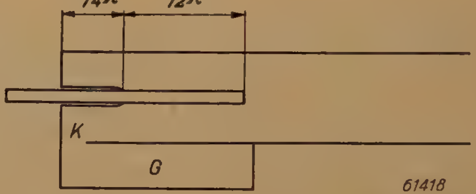


Fig. 17. Cross-section of the coaxial transmission line of fig. 16*b*. At resonance the inner conductor is $^3/_4$ wavelength long, the sliding contact being at $^1/_4$ wavelength from the short-circuited end of the outer conductor. The waveguide *G* (the longitudinal direction of which is at right angles to the plane of the drawing) is coupled to the wavemeter by the window *K*. The transmission line is open-ended at the right; by suitable choice of the dimensions of the system the waves are prevented from being propagated in the right-hand part of the cylinder, where there is no inner conductor.

Summary. After explaining the necessity of employing waveguides in microwave installations for high powers, consideration is given to the problems arising from the use of these waveguides. Discontinuities, bends and faulty matchings in the waveguide cause reflection of the electromagnetic waves; these reflections have to be avoided as far as possible, and it is therefore necessary to be able to measure the reflective properties of a waveguide section. The effect of discontinuities in the waveguide is explained by comparison with a transmission line. Owing to reflection a standing wave is formed; the absolute value of the reflection coefficient is determined by measuring the voltage standing-wave ratio (V.S.W.R.) in the wave-guide.

For measuring the V.S.W.R. a waveguide section is used in which the electric field can be determined from point to point with the aid of a probe. In addition to a probe sliding along the guide it is also possible to employ a fixed probe; by "squeezing" the guide one can change the wavelength of the oscillation in the waveguide and thus cause the field to be displaced past the probe. Such a V.S.W.R. meter is only suitable for measuring fairly small standing-wave ratios. To determine roughly the correct matching of a waveguide section, use is made of a directional coupler, with which the strength of a signal travelling in one direction can be measured.

Finally the accessories of the measuring device are dealt with separately; brief descriptions are given of the construction of the generator for the microwaves, of the attenuator, of the crystal detector rectifying the high-frequency signal, and of the wavemeter for measuring the frequency of the oscillations.

ON ELECTRICAL SHAVING

by A. Th. van URK.

672.715.3-83.004.13

While shaving, one may well ponder about such questions as to how exactly the hairs of the beard grow, how fast they grow in a day, how thick they are and how many cover a square centimetre of the skin. It is the knowledge of such matters as these, supplemented by experiments relating particularly to electrical shaving, that forms the basis for the rational construction of an electric dry-shaver.

Skin and hair

The human skin, a cross-sectional diagram of which is given in *fig. 1*, consists of three layers: the outer skin, or epidermis, the leathery skin, or corium, and the lower skin, or subcutis. As far as shaving is concerned it is of course mainly the outer skin that we have to deal with. This is a mucous membrane built up in a number of layers, with the cells gradually migrating to the surface, where they become flattened out parallel to the surface

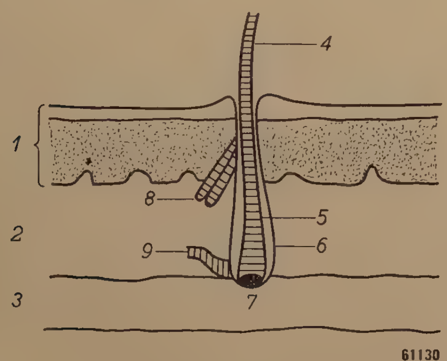


Fig. 1. Cross section of a part of the human skin, with a diagrammatic representation of a hair. *1* epidermis, *2* corium, *3* subcutis, *4* hair shank, *5* root of the hair, *6* hair sac, *7* hair papilla, *8* sebaceous gland, *9* hair muscle.

and ultimately are cast off in the form of horny scales. Consequently there are two main layers in the outer skin. The lower one is formed of living cells which continuously divide themselves, and it is therefore called the germinative layer, or stratum germinativum. The other is a surface layer, called the horny skin, or stratum corneum, which acts as a protective covering; it consists of cells that are no longer capable of dividing themselves.

There is a very intimate connection between the outer skin and the corium, on account of the finger-shaped spurs, called papillæ, extending from the corium into the epidermis. These papillæ contain capillary blood vessels, and as a consequence a cut extending down to the level between the epidermis and the corium is apt to cause bleeding, as is often the experience when using a razor. The thickness of the epidermis on the cheek of an adult is between 90 and 120 microns, i.e. about one-tenth of a millimetre. The papillæ do not extend more than about 8 microns into the epidermis of the cheek.

The hairs of the beard of an adult male are formed in the skin. The part protruding from the skin is the hair shank, the scapus pili, whilst the part hidden in the skin is called the radix pili, or the hair root. As shown in fig. 1, this root is contained in a sac or follicle, called the folliculus pili, which is embedded in the mucous membrane of the epidermis and in the corium and sometimes extends down into the subcutis. At the bottom of the hair sac is the hair papilla, bulbus pili, a spherical protuberance out of which the hair grows. Finally, at the side of the hair sac are sebaceous glands feeding the hair with fat, and below these is a muscle, the musculus arrector pili, which enables the hairs to erect themselves at times, or, as the saying goes, to stand on end.

It has been found that the daily growth of the hairs forming the beard varies between 0.2 and 0.6 mm, averaging 0.4 mm.

Density of the beard

To form an idea of the density of the beards of various people, photographs have been taken of parts of the beard of a number of test persons and from the greatly magnified photographs the numbers of hairs per square centimetre have been counted. As is only to be expected, these numbers differ considerably, as is evident from the following figures:

on the chin: 40 - 100 - 120 - 100 - 110 - 110 - 70 - 80 - 90 - 100 - 70 - 90 - 90 - 70, averaging 90 hairs per cm^2;

on the cheek: 45 - 60 - 70 - 85 - 70 - 60 - 60 - 80 - 35 - 80 - 50 - 55 - 35 - 40, averaging 60 hairs per cm^2.

In a beard there is therefore on an average no more than one hair per mm^2 (by way of comparison, the density of the hair on top of the head can be

taken as 3 hairs per mm². According to these results [1]) and taking into account the area covered by the growth of beard, a normal beard has about 13,000 hairs.

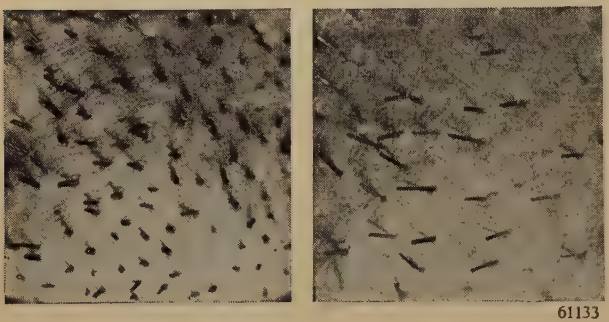


Fig. 2. Magnified photographs of part of the beards of two test persons. Left: part of the chin, 110 hairs per cm²: right: part of the cheek, 35 hairs per cm².

Two of the photographs mentioned above are reproduced in *fig. 2*.

Thickness of the hairs

For the construction of a shaving apparatus it is of essential importance to know the maximum thickness of the beard hairs: it is obvious that the minimum width of the slots or holes of the apparatus into which the hairs have to be drawn before they are cut has to be greater than the maximum thickness of hair likely to be met with.

This has been investigated by taking 31 "shavings" and measuring the thickest hairs found in them. The results are graphically represented in *fig. 3*. It appeared that the maximum thickness most commonly occurring was 0.14 mm. In about 90% of the number of shavings examined the maximum thickness of the hairs in any one of them proved to be less than 0.18 mm.

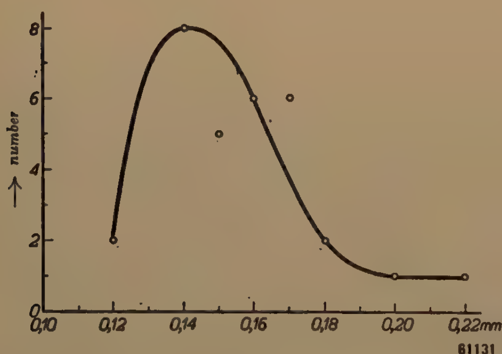


Fig. 3. The greatest thickness of the hairs contained in each of 31 "shavings" was determined. For each value it has been plotted how many times it occurred as maximum value. It appears that in about 90% of the shavings examined the maximum thickness of hair is less than 0.18 mm.

It is also possible to get some idea of the average thickness of beard hairs. The average weight of 24 "Philishave" shavings from a beard growth of 24 hours was found to be 28 mg. Taking the numbers of hairs in a beard at 13,000, as previously calculated, with an average length of 0.4 mm, and reckoning the specific gravity of hair as being approximately 1, the average thickness of the hairs in an average beard works out at about 0.07 mm.

The hair "streams" in a beard

The roots of practically all hairs are planted obliquely in the skin. From this, and the fact that neighbouring hairs stand at an angle to the surface of the skin in almost the same direction, it follows that the hairs of the beard grow in different directions, depending on what part of the face they are growing. We therefore speak of hair streams. In these streams the directions of the hairs are nearly always at a small angle to each other, and thus, instead of being parallel,

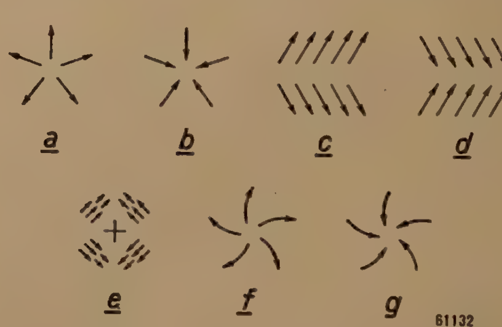


Fig. 4. Various examples of "hair streams" occurring in the human beard: *a*) stream with a centre of radiation, *b*) stream with a centre of attraction, *c*) diverging and *d*) converging stream, *e*) cross-shaped growth, *f*) diverging and *g*) converging eddy stream.

converge or diverge. Indicating the directions of the "stream lines" by arrows, we get diagrams greatly differing in shape, some examples of which are given in *fig. 4*.

These hair streams, which are characteristic for each individual, have to be taken into account when shaving, because shaving against the stream is more effective than shaving with the stream. When shaving electrically one instinctively feels how the direction of movement of the shaving head has to be changed, according to what part of the face is being shaved; sometimes the shaving head has to be moved in a straight line and sometimes it has to be rotated.

---

[1]) The figure of 40 hairs per cm² sometimes found in the literature on the subject is apparently based on inaccurate data.

Construction of the "Philishave" dry-shaver

Having now said something about the growth of the hairs of the beard, we shall consider how these facts can be taken into account in the construction of a dry-shaver, in this case the "Philishave" dry-shaver [2]).

This apparatus consists of a stationary part, the shaving cap, which is pressed against the skin and has a large number of slots into which the hairs are guided, and a moving part that cuts off the hairs. The latter part has a rotating motion, and not an oscillating motion as in the case of a pair of clippers. It consists of a six-fold milling cutter rotating at a high speed and pressed gently by a spring against the inner face of the stationary cap.

Compared with the oscillating movement, the rotating motion has the advantage that a very much higher cutting speed can be reached, this being helped by the presence of the six-fold cutter. The cap has been given such a diameter that the whole of its surface can always be in contact with the skin. A secondary advantage, but not unimportant from the hygienic point of view, of the construction of this apparatus is that the hairs which have been cut off are collected in the cap instead of being allowed to fly about. This apparatus and some of its component parts are illustrated in *fig. 5*.

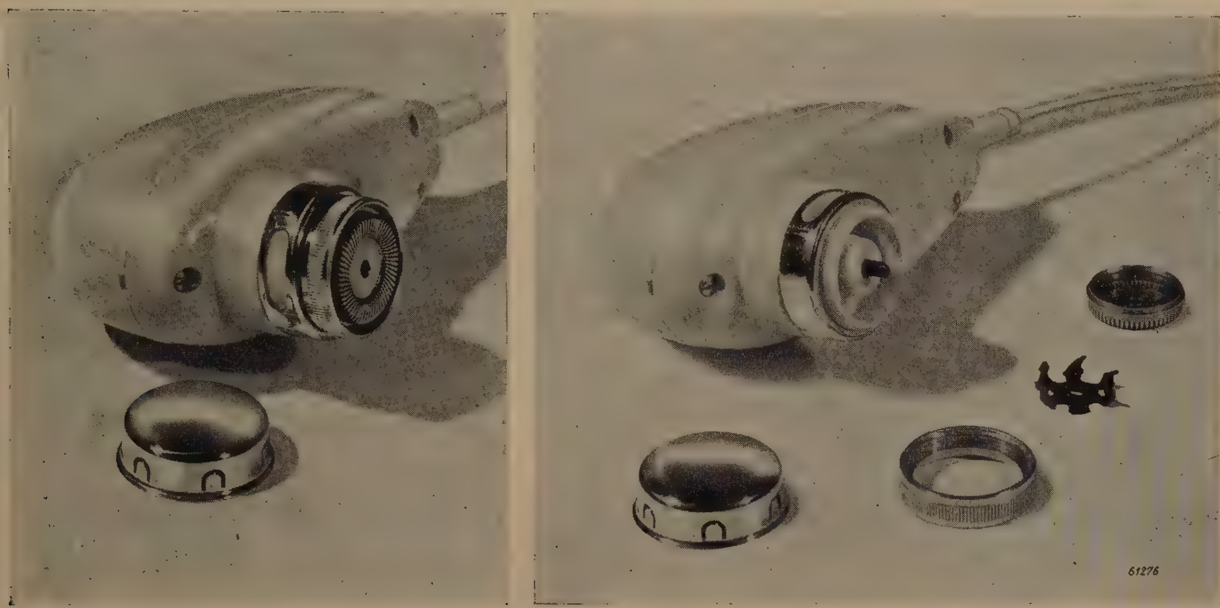


Fig. 5. On the left the "Philishave" dry-shaver and the guard cap. On the right the same but with the shaving cap and cutter detached.

What one desires with a shaving apparatus is to be able to shave quickly and cleanly, without any risk of injuring the skin. In this respect the width of the slots and the thickness of the cap where the cutter is rotating are particularly important.

Let us first consider the width of the slots. We have seen that the average thickness of the beard hairs is 0.07 mm, but to be able to catch also the thickest hairs the slots must in any case be wider than 0.18 mm. The wider the slot the greater the chance of catching the hairs, since roughly speaking this chance is proportional to the difference between the width of the slot and the thickness of the hair. For quick shaving, therefore, a fairly wide slot is desired. On the other hand, however, if the slot is too wide there is a risk of the skin bulging out too far into the slots — a point which will be further dealt with presently — and thus suffering damage. A width of about $^1/_4$ mm appears to be a good compromise.

The slots on the inside of the shaving cap, where the cutter describes its circular path, are extended to the edge of the cap (see fig. 5) and join up with the guiding grooves in the cylindrical wall of the cap. In order to ascertain how and where the hairs enter the slots, film photographs were taken of a beard rubbing over a shaving cap. When the test

---

[2]) A description of this apparatus was given by A. Horowitz, A. van Dam and W. H. van der Mei, "The dry-shaving apparatus "Philishave", Philips Techn. Rev. 4, 350-354, 1939. In the design described in that article a three-fold milling cutter was used, but the more recent designs have a six-fold cutter.

person rubs his cheek over the cap at a rate of say 10 cm per second and the slots are 0.25 mm wide, a hair will pass across the slot in about 1/400th of a second. A normal film camera taking 24 pictures per second is therefore not suitable for showing how a hair is caught up in the slot. Consequently a camera with a very high speed had to be used, taking up to 3000 pictures per second. A magnified cut from one of the films is reproduced in *fig. 6*. This investigation showed, inter alia, that long hairs enter the slots mainly via the guiding grooves, while shorter ones may appear anywhere in the slot.

The second important factor mentioned above was the thickness of the shaving cap. At first sight one would be inclined to say that the thinner the cap the better it is — provided it remains sufficiently rigid — because with a thin cap the hairs will be cut off closer to the skin than is the case with a thicker one. Actually, however, what takes place is that the skin, which is more or less supple, bulges out into the slots and thus helps in cutting the hairs off short. But since it is not desirable for the skin to penetrate too far into the slots, as we have already seen, on that account alone a limit is set to the thinness of the shaving cap, apart from the question of rigidity.

An investigation has also been made to see in how far the skin tends to bulge out into the slots. The device used is illustrated in *fig. 7*. From the results obtained it appeared that the extent of penetration (thus the suppleness of the skin)

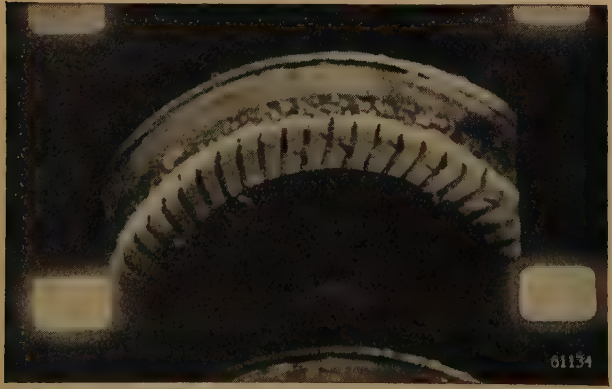


Fig. 6. One of the pictures from a cinematographic film showing how the hairs of a beard are caught up in the shaving cap of a "Philishave" dry-shaver.

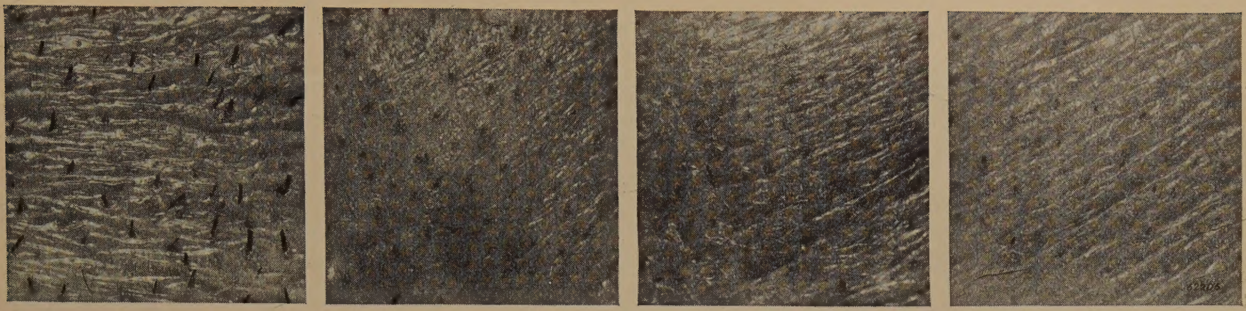
not only differs considerably as between one person and another but also shows rather great differences for the same person between the various parts of the face (cheek, chin, neck). Naturally the extent of penetration also depends for a great deal upon the force with which the shaving cap is pressed

61135

Fig. 7. Microscope set-up used for measuring the extent to which the skin bulges out when shaving with a dry-shaver. The shaving cap is centred in the round glass cap at the front of the apparatus, and is illuminated from the inside by a number of small lamps placed in a circle round the objective. The microscope eye-piece is inside the cone on the right-hand side of the apparatus. The observer focuses the microscope onto the inner face of the shaving cap along which the cutters run, and then onto the skin; the displacement gives a measure for the bulging of the skin.

against the skin, but when using the apparatus one very soon acquires the "feeling" to know on what parts of the face the shaving head has to be pressed down more or less heavily in order to get a clean shave. In the light of these considerations, with a slot width of $^1/_4$ mm about 0.1 mm is found to be the most suitable thickness for the material of the shaving cap.

Finally, in *fig. 8* four enlarged photographs are given of part of the beard of a test person shaved in three different ways, viz. with a safety razor, by a barber with an ordinary razor and with a "Philishave" dry-shaver. In all three cases the face is sufficiently clean-shaven (disregarding the single hair accidentally left by the barber, photo *c*). In the case of photo *b* it may aptly be said that the "safety" razor has shaved off the beard "with hide and hair", whereas photo *d* shows that the "Philishave" dry-shaver — thanks to the carefully cal-



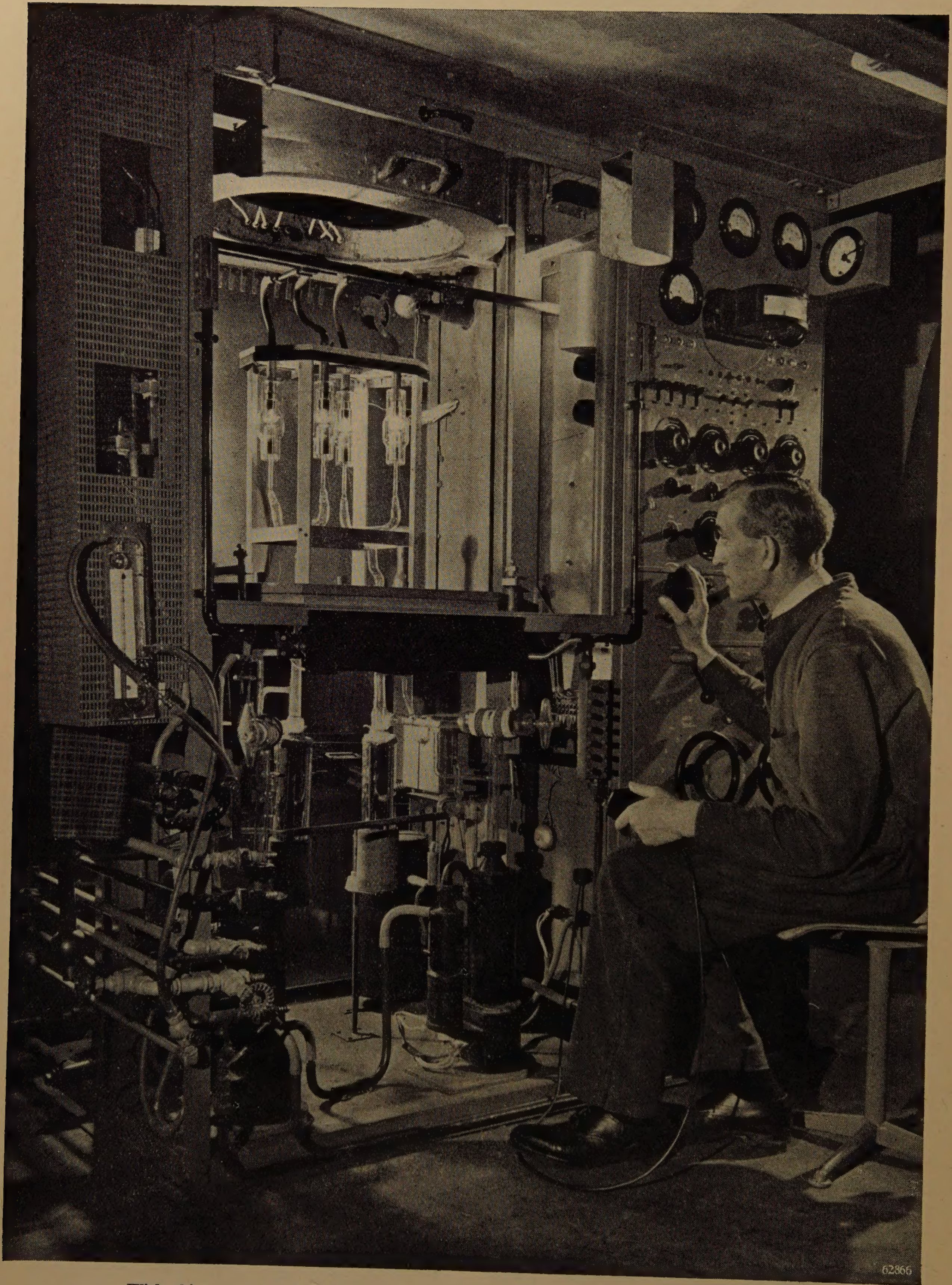
a *b* *c* *d*

Fig. 8. The same part of the beard of a test person, 8 times enlarged, *a*) before shaving, *b*) after shaving with a safety razor, *c*) after being shaved by a barber, *d*) after shaving with a "Philishave" dry-shaver.

culated dimensioning of the shaving head — has left the original structure of the skin practically untouched, better even than the professional barber with his razor.

Summary. From data obtained from the literature on the subject and from his own observations the writer gives a brief account cf the growth of the hairs of the beard. The number of hairs in a normal beard amounts to about 13,000 and the growth per day is about 0.4 mm. The maximum thickness of the hairs has been found to be 0.18 mm and the average thickness 0.07 mm. For quick and clean shaving with the "Philishave" dry-shaver the width of the slots and the thickness of the material of the shaving cap are of primary importance. It is described how, with the aid of a high-speed camera taking up to 3000 pictures per second, a study has been made of the manner in which the hairs of the beard are caught up in the shaving cap. A brief description is also given of the means employed for measuring the extent to which the skin bulges out into the slots when shaving.

PUMPING OF X-RAY TUBES



With this apparatus four X-ray tubes (diagnostic tubes for 110 kV, of the "Statix" type) are pumped simultaneously. The elliptical oven seen raised above the tubes can be lowered over them for heating the tubes to the temperature required for degassing.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS OF THE N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of these papers not marked with an asterisk can be obtained free of charge upon application to the address printed on the back cover.

1892: J. Haantjes: A self-oscillating line-deflection circuit (Bull. S.E.V. **40**, 633-635, 1949, No. 1).

Description of a self-oscillating circuit in which, apart from a short fly-back time, the voltage is a linear function of time. Schematically the circuit may be represented by a self-inductance L and a capacitance C connected in parallel to a battery via a switch. If the switch is periodically opened for a short time, equal to the time of one half oscillation of the circuit, oscillations of the desired properties will occur. In the article it is shown how the switch may be realised by a combination of a diode and a triode. By a slight modification the internal resistance of the switch may be lowered. Some other alterations are described, which allow the circuit to be synchronized, on the control grid, with negative pulses of a few volts from a source of rather high internal impedance (see Philips Techn. Rev. **10**, 307-317, 1948).

1893: J. A. Lely and T. W. van Rijssel: X-Ray collimator producing a beam of very small divergence and large intensity (Acta crystallographica **2**, 337, 1949, No. 5).

Short description of an X-ray collimator, consisting of two polished glass bars, 120 mm long, placed almost parallel to each other (distance at one end 9 μ, at the other end 140 μ) and cemented between two glass plates. The narrow opening is placed as close as possible to the focus of the X-ray tube.

The primary beam entering through the slit is rendered parallel by multiple total reflections against the polished surfaces. In this way beams may be obtained with a divergence of only a few arc minutes, which suffices to measure lattice distances of 350-400 Å. With a slit the gain in intensity is 3-5 times and with a square aperture (pinhole) 10-30 times.

1894: E. J. W. Verwey: Nouveaux matériaux céramiques (Bull. Soc. Chim. France, Mars-Avril 1949, p. D 120-121). (New ceramic materials; in French.)

Survey of modern synthetic ceramic materials, which are used in electrotechnical engineering for their special dielectric, magnetic or conductive properties. Special attention is paid to the spinels containing iron (XFe_2O_4). See Philips Techn. Rev. **9**, 186-191, 239-248, 1947).

1895: E. J. W. Verwey: Valence induite (Bull. Soc. Chim France, Mars-Avril 1949, p. D 122). (Controlled valency; in French.)

By introducing monovalent ions (e.g. Li_2O) into a lattice of trivalent ions (e.g. NiO) a certain fraction of these ions passes into the trivalent state during the formation of the solid solution in equilibrium with an atmosphere containing oxygen. By this process the originally non-conducting oxide becomes a semiconductor, the conductivity of which can be easily controlled.

1896: E. J. W. Verwey: Arrangement des cations dans les spinelles (Bull. Soc. Chim. France, Mars-Avril 1949, p. D 123). (Cation arrangement in spinels; in French.)

The lattice energy of spinels is calculated as a function of small variations of the distance of the oxygen ions for different cases of occupation of the tetrahedral and octahedral interstices. Certain special cases are discussed in detail (see No. **1894** of these abstracts).

1897: W. Elenbaas and E. W. van Heuven: Water-cooled high-pressure mercury-discharge lamp for direct-current operation (J. Soc. Motion Picture Eng. **53**, 594-597, Nov. 1949).

A water-cooled high-pressure mercury-vapor lamp operated on direct current which has been used for motion picture projection is described. When mounted in a suitable reflector it is a powerful light source for high-speed photographic applications. The lamp has a bore of somewhat less than 2 mm and an arc length of $12^1/_2$ mm. It can be operated continuously at 1000 watts and has a brightness of about 320,000 candles per square inch along the axis of the arc. With the reflector described, an area 5 inches in diameter can be illuminated to 50,000 foot-candles with one lamp unit. With a lamp of double length consuming 2 kilowatts the illumination level may be increased considerably.

1898: P. C. van der Willigen: Lasbaarheid van zacht staal en laaggelegeerd staal (Lastechniek **15**, 317-322, 1949, No. 12). (Welding properties of mild steel and low alloy steel; in Dutch.)

From equilibrium diagrams of iron with different admixtures, such as Fe-S, Fe-P, Fe-H, Fe-N and Fe-O, the influence of these admixtures on the weldability of mild steel and low alloy steel is discussed; the part played by hydrogen from the electrode-coating is considered.

R 125: J. te Winkel: A note on the maximum feedback obtainable in an amplifier of the cathode-feedback type (Philips Res. Rep. **5**, 1-5, 1950 No. 1).

The total feedback on the last valve in a feedback amplifier is calculated for the case that the feedback voltage is derived from an impedance inserted between the cathode of the last valve and earth (cathode feedback). This quantity is shown to have an upper limit which depends only on the frequency and on the ratio of the transconductance and input capacitance of this last valve; the total feedback also appears to be invariably less than the product of the individual feedback of the valve and the feedback around the main loop.

R 126: J. L. H. Jonker: Valves with a ribbon-shaped electron beam: contact valve; switch valve; selector valve; counting valve (Philips Res. Rep. **5**, 6-22, 1950, No. 1).

This paper describes some of the results obtained in investigations with the object of developing cathode-ray tubes with ribbon-shaped electron beams suitable for purposes such as high-speed switching. By comparing the physical characteristics of the more common beams of circular cross-section with those of a ribbon-shaped beam, it is shown that by employing the latter the size of the tubes can be so much reduced that the customary radio-valve techniques can be applied in their construction. The new possibilities thus created are illustrated by (1) an electronic contact valve, which may serve as a telephonic switch, (2) a valve of similar design for replacing magnetic relays in central telephone stations, (3) a valve operating as a multi-contact switch, and (4) a valve capable of recording at a high speed a number of pulses fed to one of its electrodes.

R 127: J. M. Stevels: Some experiments and theories on the power factor of glasses as a function of their composition, I. (Philips Res. Rep. **5**, 23-36, 1950, No. 1).

For a number of series of glasses in which the composition is varied systematically, the power factor ($\tan \delta$) and the dielectric constant at 20 °C and for a frequency $f = 1.5 \times 10^6$ c/s have been measured.

R 128: J. D. Fast: The gas phase in equilibrium with a solution of carbon, oxygen, hydrogen and nitrogen in liquid iron (Philips Res. Rep. **5**, 37-45, 1950, No. 1).

From data available in the literature the composition of the gas phase in equilibrium with a dilute solution of C, O, H, and N in liquid iron is computed. In the range of temperatures from 1800 °K to 2000 °K the equilibrium pressures are approximated by formulae of the type

$$\log \frac{p_{A_nB_m}}{[\%A]^n[\%B]^m} = -\frac{C}{T} + D \quad . \quad . \quad . \quad (6)$$

where T is the absolute temperature and where the % figures indicate weight percentages of the various elements in the liquid. The form A_nB_m indicates the different gases (CO, CO_2, H_2, H_2O, CH_4 and N_2).

R 129: K. Rodenhuis: The limiting frequency of an oscillator triode (Philips Res. Rep. **5**, 46-77, 1950, No. 1).

This paper discusses the theoretical evaluation of the "limiting frequency", that is, the highest frequency at which a triode is capable of oscillating. A triode is considered as a four-terminal network. General conditions are derived that must be satisfied by the four-pole coefficients in order that a four-terminal network shall be able to deliver power to an external circuit; these are then identified with the oscillatory condition of a triode. The relations existing between the four-pole coefficients of a triode on the one hand, and the properties of the electron current, the series resistances in the electrode leads, the resistance of the emissive coating, and the dielectric losses in the insulators on the other hand, are established and discussed. Finally the theory is applied to the ultra-short-wave oscillator triode EC 81 where the calculated limiting frequency is found to be 15% in excess of the limiting frequency observed. This discrepancy can be attributed to the approximations in the theory. The relative importance of various factors is clearly brought out by the calculations. In a concluding section the experimental determination of the limiting frequency is briefly described.